Voltage Stability Analysis and Congestion Management

Ph.D. Thesis

SAURABH RATRA

(Enroll. ID 2013REE9505)

DEPARTMENT OF ELECTRICAL ENGINEERING

MALAVIYA NATIONAL INSTITUTE OF TECHNOLOGY JAIPUR

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Saurabh Ratra

(Enroll. ID 2013REE9505)

Under the Supervision of

Prof. Rajive Tiwari

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DEDICATIONS

This thesis is dedicated to my parents for their ever loving support over the years. My thanks to my sister Divya, brother in-law Sandeep and niece Saanvi.

Declaration

I, Saurabh Ratra (I.D. No. 2013REE9505) declare that this thesis titled, "Voltage Stability Analysis and Congestion Management" and work presented in it is my own, under the supervision of Dr. Rajive Tiwari, Department of Electrical Engineering, Malaviya National Institute of Technology, Jaipur (Rajasthan),India.
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This is to certify that the thesis entitled "Voltage Stability Analysis and Congestion Management" by "Saurabh Ratra" (Enroll. ID 2013REE9505) to Malaviya National Institute of Technology, Jaipur for the award of the degree of Doctor of Philosophy in Electrical Engineering is a bonafide record of original research work carried out by him out under my supervision and that it has not been submitted elsewhere for a degree.

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ii. Mr. Saurabh Ratra has fulfilled the requirements for the submission of this thesis.

Prof. Rajive Tiwari

Supervisor
Department of Electrical Engineering
Malaviya National Institute of Technology Jaipur

Place: Jaipur
Date:

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(Saurabh Ratra)

Abstract

The deregulation of power in electric industry has resulted in overexploitation of transmission and generation services and therefore, the existing power systems are operating under stressed conditions. The stressed conditions of network lead to voltage instability which manifest as reduction in voltage at certain buses. The possible consequence of voltage instability is voltage collapse that leads to blackouts and loss of economy. Therefore, assessment of voltage stability is quite essential for a maintaining reliability and security of power systems.

The present operating state and voltage stability margin can be identified by using voltage stability indices. Numerous voltage stability indices have been presented in the literature to detect the voltage-weak lines/buses. Lot of these indices is obtained using approximate transmission line model where line resistance and charging capacitance have been ignored. Moreover, most of the voltage stability indices are complex; they require many parameters to assess voltage stability. Majority of these indices are not mapped to measure voltage stability margin. Beside this, majority of the indices fail to prove that at maximum loading point, load impedance is equal to Thevenin's impedance at the corresponding load terminal. Considering these limitations, a novel voltage stability index is proposed for accurate analysis of voltage stability. The proposed index is tested on standard IEEE bus systems. The weak lines and stability margin are estimated on the basis of proposed index. The proposed technique predicts more accurate results in comparison to other voltage stability indices. It is also observed that proposed index is mapped to compute the voltage stability margin in terms of MVA under various systems and operating conditions and accuracy is validated by comparing it with actual margin.

The voltage collapse phenomenon can be associated to the action of tap changers of transformers. The operation of on line tap changers (OLTCs) has a significant impact in planning and operation of today's power system. Many researchers have proposed different methods to coordinate OLTCs with other devices for voltage stability improvement. Very little work has been stated in the literature about critical OLTC identification. Majority of the methods are based on optimal tap settings of OLTCs for better operation of power system, but the methods are unable to identify critical transformer. In view of the above, this thesis presents a new index which detects the critical transformer. The proposed index is investigated on standard IEEE bus systems. The proposed index identifies the critical transformer. Once, the critical transformer is identified voltage stability problem can be sorted out by providing reactive power support using flexible ac transmission system

(FACTS) devices. Appropriate allocation of FACTS controllers at weak buses is the most effective way to enhance the voltage stability of the power systems.

Different studies have been carried to coordinate OLTC operation and to allocate FACTS devices. Many researchers have proposed different artificial intelligence (AI) techniques to coordinate OLTC operation with FACTS devices for voltage stability improvement. These AI techniques use complex search methods for optimization. Moreover, these methods use iterative trial and error progress with large data sets which are time- consuming. To cope up the problem, an efficient and reliable optimization procedure based on fuzzy and Taguchi method (TM) has been proposed for coordinating OLTC tappings and FACTS devices, which minimizes transmission loss while maintaining the quality of voltages.

Finally, the thesis investigates the optimal placement of distributed generator (DG) and FACTS devices for congestion mitigation and voltage stability improvement. A new index is developed to measure the degree of congestion in transmission lines. Moreover, a multi-objective fuzzified TM has been proposed in the thesis to find optimum sizing of DG and FACTS devices. Effectiveness of each device has also been investigated for optimization of single objective. DG is observed to be the most prominent solution for alleviating congestion in transmission lines, but its effect on voltage stability is less noticeable. Conversely, FACTS devices improve the voltage stability, but congestion mitigation is less noticeable. Most effective solution of multi-objective problem is observed when DGs and FACTS devices are coordinated optimally.

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Abbreviations

AI	**A**rtificial **I**ntelligence
CFP	**C**onsistent **F**unctioning **P**oint
CPF	**C**ontinuation **P**ower **F**low
CPT	**C**onstant **P**ower **T**ype
DG	**D**istributed **G**enerator
EHV	**E**xtra **H**igh **V**oltage
ELSI	**E**xtended **L**ine **S**tability **I**ndex
FACTS	**F**lexible **A**lternating **C**urrent **T**ransmission **S**ystem
GVSM	**G**lobal **V**oltage **S**tability **M**argin
LSI	**L**ine **S**tability **I**ndex
LQP	**L**ine **S**tability **F**actor
MLI	**M**aximum **L**oadability **I**ndex
MLP	**M**aximum **L**oading **P**oint
MSV	**M**inimum **S**ingular **V**alue
MVAr	**M**ega **V**olt **A**mpere **r**eactive
MW	**M**ega **W**att
NR	**N**ewton **R**aphson
OA	**O**rthogonal **A**rray
OLTC	**O**n **L**oad **T**ap **C**hanger
POC	**P**oint **O**f **C**ollapse
PSO	**P**article **S**warm **O**ptimization
SOA	**S**eeker **O**ptimization **A**lgorithm
STATCOM	**S**tatic **S**ynchronous **C**ompensator

SVC	**S**tatic **V**ar **C**ompensator
TM	**T**aguchi **M**ethod
VCPI	**V**oltage **C**ollapse **P**roximity **I**ndicator
VSLI	**V**oltage **S**tability **L**oad bus**I**ndicator
VSI	**V**oltage **S**tability **I**ndex
VSM	**V**oltage **S**tability **M**argin

Symbols

P_R	Receiving end active power
Q_R	Receiving end reactive power
V_S	Sending end voltage
V_R	Receiving end voltage
A	Transmission line parameter
X	Reactance of line
R	Resistance of line
Z	Impedance of line
Y	Line charging admittance of line
I	Current in transmission line
θ	Impedance angle of line
β	Angle part of transmission line parameter B
δ	Phase angle difference between sending and receiving end voltages
α	Angle part of transmission line parameter A
λ	Load multiplication factor
λ_{max}	Maximum loadability factor
l	Maximum number of lines
V_{Sj}	Sending end voltage of j^{th} line
V_{Rj}	Receiving end voltage of j^{th} line
A_j	Transmission line parameter of j^{th} line
β_j	Angle part of transmission line parameter B of j^{th} line
α_j	Angle part of transmission line parameter A of j^{th} line
δ_{SRj}	Phase angle difference between sending and receiving end voltages of j^{th} line

t	tappings of OLTC
R	Resistance of Line
P	Active power
X	Reactance of Line
Q	Reactive power
V_S	Sending end voltage
V_R	Receiving end voltage
μ^F	Fuzzy Membership Function
μ^P	Membership function for real power loss
μ^F	Degree of overall fuzzy satisfaction
μ^{CMI}	Membership function for CMI index
μ^L	Membership function for L-index

Chapter 1

Introduction

For many years power system designers and operators had been concerned about rotor angle stability for maintaining synchronism in the power systems. The problem of rotor angle stability is well recognized and reported in [1]–[2]. However, nowadays with economic liberalizations, there is swift increase in load demand but restriction on building new transmission and generation facilities due to environmental constraints, deregulation policies, etc.; have forced the power systems to operate under stressed condition. The stressed condition have led power system to face another kind of stability problem, which manifest as slow or sudden fall of voltage at some buses. The problem is referred as voltage stability problem of power systems [3]-[15].

1.1 Voltage Stability Background

Voltage instability is of increasing importance to utility companies. Voltage instability or collapse is characterized by a progressive fall of voltage which can take several forms. The main factor is the inability of the network to meet a demand of reactive power. The process of instability may be triggered by some form of disturbance. The disturbance may be in the form of small or large changes in load demand. The consequence of voltage instability may, however, have a wide spread impact. During last few decades many voltage collapse phenomenon have been observed worldwide [16]-[21]. It has become a serious threat to reliability and security of the power systems.

The voltage stability can be classified as static and dynamic [22]-[23]. Dynamic analysis of voltage stability involves time domain simulations which is time consuming. Besides this, they do not deliver readily sensitivity information or the degree of voltage instability hence, it is unsuitable for practical operation of power systems. Conversely, the static voltage stability problem is investigated through steady-state models and techniques [24]; these practices are fast and permit an operator to take fast counteractive decisions. The outcomes of such studies may be used to identify available MW/MVAr margins of the power systems [25]. Static analysis provides much understanding into problem of voltage stability.

1.2 Voltage Stability Indices

Traditional method uses P–V and Q–V curves [26]-[27] to identify static voltage collapse point. However, this technique consumes a large computational time due to repetition of power flow. This has led to the growth of voltage stability indices for fast estimation of voltage collapse point. These indices are broadly used as a tool for assessment of the voltage stability of power systems. The indices used for voltage stability analysis may be classified as: Jacobian matrix based indices [29]-[47], bus voltage stability indices [58]-[64], and line voltage stability indices [65]-[74]. Singular value minimization of Jacobian matrix is used as a pointer of voltage stability in Jacobian based indices whereas bus/line voltage stability indices assess voltage stability state of the system on the basis of data of bus voltages and line flows.

A heavy loading on transmission network may lead to voltage collapse when it reaches under critical state. Thus, the loading stress on transmission lines must be constantly observed so that necessary precautionary measures can be taken in advance to make system secure. Line stability indices can be used to find critical lines and to observe their stressed conditions. Numerous line stability indices have been proposed in the literature [65]-[74] to monitor the present state of critical lines. Most of these voltage stability indices are complex in nature and neglects line resistance and shunt branch parameters which lead to inaccuracy in prediction of voltage stability status of the system. Moreover, most of the existing voltage stability indices have not been mapped to measure the available MW/MVA margin. Besides this, majority of the indices fail to prove that at maximum loading point, load impedance is equal to Thevenin's impedance at the corresponding load terminal. Therefore, it is necessary to develop an accurate index which can predict the severity of voltage stability state and available voltage stability margin precisely.

1.3 OLTC

It is important to note that the voltage stability of the system is sensitive to the tap changing operation of on-load tap changers (OLTC). With each tap change operation, the MW and MVAR loading on the EHV lines would increase, thereby increasing the reactive power loss and causing higher voltage drops. As a result, with each tap-changing operation, the reactive output of generators throughout the system would increase gradually and the generators may hit their reactive power capability limits, causing voltage instability problems. The problem can be sorted out by providing reactive power support using shunt capacitors or flexible ac transmission system (FACTS) devices. Many researchers have proposed different artificial intelligence techniques to coordinate OLTC operation with other devices for voltage stability improvement [76]-[131]. These methods use iterative trial and error progress with large data sets which are time- consuming. Moreover, these methods also stuck to local minima. Therefore, a reliable technique is required for optimal coordination of OLTC operation with FACTS devices. Moreover, very little attention has been devoted in the literature to identify the critical transformer that initiates the voltage instability.

1.4 Optimal Locations of DG and FACTS

Line congestion also leads to voltage instability [132]-[141]. Lines can be relieved from overloading conditions by placing distributed generators (DGs) and FACTS devices of optimal size at appropriate locations. Optimal allocation and coordination of renewable

DG and FACTS devices is an important aspect for mitigating congestion and enhancing the performance of power system. Improper placement of DG and FACTS devices not only fails to optimize the performance of power systems but also produce undesired results. The FACTS devices can be placed either at weak buses/lines on the basis of voltage stability indices or optimum locations can be selected using artificial intelligence (AI) techniques. Numerous researchers have used index based methods to find locations for placing FACTS devices.

Power systems are generally very complex in nature and therefore, power system security cannot be improved by optimizing only one objective. Therefore, power system performance improvement is a multi-objective problem that necessitates enhanced voltage stability margin, decreased active and reactive power losses, etc. These objectives are different in nature and optimizing one objective may deteriorate other objectives. Therefore, to confirm a minimum degree of satisfaction for all the objectives, a multi-objective problem must be converted into a single objective. Various methods are presented in the literature to convert multi-objectives to single objective; i.e. weighted additions of different objectives, averaging of different objectives, product of different objectives etc. However, these deterministic approaches are not suitable to convert different objectives into single objective. In 1965, [142] proposed fuzzy set theory to transform multiple objectives into a single objective function. Fuzzy logic due to its nature ensures minimum degree of satisfaction among different objectives. Each objective is linked with a membership function in fuzzy domain which determines the degree of satisfaction of that objective. Fuzzy logic technique has been applied in proposed research to transform the multi-objective optimization problem which includes minimization of congestion, and enhancement of voltage stability margin, into single objective problem. A trapezoidal fuzzy membership function is used in the thesis to find out the membership values of different objectives.

Some well-established AI techniques such as; Taguchi Method(TM) [110]-[115], Particle Swarm Optimization-constriction factor (PSO-cf) [147]-[148], Seeker optimization algorithm (SOA) [147]-[149],have been proposed by researchers to solve multi-objective problems. TM has been extensively applied to solve many optimization problems in electrical machines design and electric power system, because it can handle discrete variables easily and also manages continuous variables and nonlinear objective and constraint functions [150]. TM is a statistical method, also known as robust design methods which are based on the design of orthogonal arrays (OA) to improve the performance of the system.

In the thesis work, a congestion index is developed to measure the level of congestion in transmission lines. Proposed index is then computed for different lines to identify the available MVA margin. To mitigate the problem of congestion and improving voltage stability, DGs and static synchronous compensators (STATCOM) are placed at suitable locations. Minimization of congestion index and L-index of power systems are considered objectives. A multi- objective fuzzified Taguchi method has been proposed in the thesis to determine optimal sizing of DGs and STATCOMs for relieving line congestion and improving voltage stability.

Chapter 2

Literature Survey

This thesis presents study and analysis of voltage stability and congestion management in power systems using coordination of on load tap changers (OLTCs), flexible AC transmission system (FACTS) devices, and renewable based distributed generation (DG). This section analyzes the literature of voltage stability problem, method of assessment, and remedial measures to discover proposed research work. The basics of voltage stability, assessment practices, margin enhancement, voltage stability improvement by optimal coordination of OLTCs and FACTS devices, and congestion mitigation through Distributed Generation (DG) and FACTS devices are briefly discussed in the section. The research objectives are framed based on critical review of the literature for the present work.

2.1 Introduction

The assessment of voltage stability and inhibitory control plays a salient in the operation and planning of power systems. Tracking the propinquity of power system to an uncertain voltage condition has gained significant importance. Numerous blackouts have been reported worldwide to voltage collapse [1],[4]. The main cause of these blackouts was inadequate voltage stability margins. Nowadays with economic liberalizations, there is swift increase in load demand but restriction on building new transmission and generation facilities due to environmental constraints, deregulation policies; forcing the power systems to function under stressed condition [5]. These stressed conditions, if not taken care of, leads to voltage collapse with sequential blackouts and revenue loss. Hence, there is a need for modern power systems to adopt fast and precise methods for monitoring voltage stability, which could identify the level of VSM and recommend remedial measures to confirm voltage stability under all operating conditions.

The voltage instability phenomenon is also related to the action of on load tap changers (OLTC). OLTC may lose its capability to raise the voltage after certain tap changing operation under abnormal conditions. Therefore role of OLTC must be studied to prevent the voltage collapse. Modern power system is also equipped with DGs which can play a significant role in relieving stressed condition of existing power systems. Numerous research works has been carried out in the field of voltage stability assessment and its enhancement using coordination of OLTCs, FACTS devices and DGs. Considering all these aspects, this chapter presents a literature survey of voltage stability, its assessment methods and role of OLTCs, FACTS devices, and DGs in voltage stability and line congestion. On the basis of critical analysis of the literature, research gaps have been identified and accordingly research objectives have been formulated.

2.2 Voltage Stability Definitions According to

In the literature various definitions related to voltage stability have been presented. These definitions consider system conditions, disturbances, time structures,etc. It is revealed through these definitions that there is an extensive spectrum of phenomena that could occur during voltage instability. Various task forces have defined voltage stability in the following way:

2.2.1 CIGRÉ

CIGRÉ [6] defined voltage stability in the following way:

- Power system at a given operational condition is small-disturbance voltage stable if, any small disturbance, voltages nearby loads are same or nearby to the pre-disturbance values.
- Power system at a given operational condition subject to a specified disturbance is voltage stable, if voltages close to loads approach post disturbance equilibrium values.

2.2.2 IEEE

A second set of descriptions is proposed by IEEE [7]. The subsequent definitions associated to voltage stability are given:

- Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. It depends on the ability to maintain/restore equilibrium between load demand and load supply from the power system.
- Voltage collapse is the procedure by which voltage instability tends towards loss of voltage for a major part of the system.
- Voltage security is the capability of a system, not only to function firmly, but also to maintain stablility following any contingency or adverse change in system.

2.2.3 Hill and Hiskens

Additional approach of stability definitions is suggested by Hill and Hiskens [8]. The procedure is separated into static and a dynamic part. Certain conditions for static behavior are mandatory to be stable for the system:

- Voltages must lie between permissible limits.
- Voltages in power system must be consistent functioning point (CFP). A CFP indicates that if reactive power is injected into the system or a voltage source increases its voltage, a voltage increase is expected in the network.

For dynamic part, [8] proposed the subsequent concepts:

- Small disturbance voltage stability: A power system at a specified working condition is small disturbance stable, if following any small disturbance, its voltages are identical to or close to their pre disturbance values.
- Large disturbance voltage stability: A power system at a specified working condition and subject to large disturbance is voltage stable, if the voltages reach post-disturbance stable values.
- Voltage collapse: A power system at a specified working condition and subject to large disturbance experience voltage collapse if it is voltage unstable or the post-disturbance values are infeasible.

2.2.4 Glavitch

Another set of definition is proposed by Glavitch [9]. In this approach different time frames of the collapse phenomenon are demonstrated:

- Transient voltage instability is described by a large disturbance and a sudden response of power system and its components, e.g. induction motors. The time frame is from one to few seconds which is also a period in which automatic control devices at generators react.
- Long-term voltage instability is described by a large disturbance. The time frame is within 0.5-30 minutes.

  Reference [9] also suggests a difference between static and dynamic analysis. If differential equations are involved, the analysis is dynamic. "Static does not mean constant, i.e. a static analysis can very well consider a time variation of a parameter."

Out of these described set of definitions, IEEE definition is correlated to the authentic process in the network and Hill and Hiskens appears to be close to control theory. The context in these definitions on voltage stability comprises three major concerns, i.e.

the voltage levels must be permissible; system must be controllable in the operating state; and it must survive a contingency.

2.3 Voltage Stability Assessment Methods

Numerous classical methods are available in the literature to identify voltage stability margin and point of collapse (PoC) of existing power systems. The indexing on voltage stability [10] is publicized in 1998. It is well known fact that PoC is system loadability limit which can be measured through repeated power flow solution by increasing the load until the load flow solution diverges. The significant outcome of the early research work based on repeated power flow was PV and QV curves [26]-[27] . However, beyond the nose point of the P-V curve, the load flow does not converge. The convergence problem was sorted by continuation power flow (CFP) [28]. But this method requires repeated power flow solution and therefore it is time consuming. It has led to development of voltage stability indices for quick estimation of voltage collapse point. These indices derive a scalar value from the parameters of power systems that is an indicator of voltage stability state of the system.

Various voltage stability indices have been proposed in the literature. The indices used for analysis of voltage stability can be categorized as: Jacobian matrix based indices, bus voltage stability indices, and line voltage stability indices.

Jacobian matrix based indices use minimum singular value of the Jacobian matrix as an indicator of voltage stability while bus and line voltage stability indices are computed on the basis of power flow results.

Voltage stability indices based on Jacobian matrix evaluate the state of voltage stability using Jacobian matrix of power flow. System will at the verge of voltage instability state when Jacobian matrix becomes singular. The concept of singularity of Jacobian matrix was introduced by Venikov *et al.* [29] who proposed that the sign of determinant of the Jacobian matrix is an indicator of voltage stability of the system. Thomas *et al.* [30] suggested that the minimum singular value of the Jacobian matrix can serve as a voltage stability index. The minimum singular value is a measure of distance from steady-state voltage stability limit.

In [31], expanded newton raphson seydel (NRS) method which is based upon Jacobian matrix is proposed to find voltage stability state. This method is found to be more suitable for distribution systems due to its insensitivity to r/x ratio of the system. Chiang *et al.* [32] proposed a test function to forecast the point of collapse. The test function is based on Jacobian matrix. In [33], Gao *et al.* proposed bus participation factor to find weakest bus of the system. Bus participation factor is found using smallest eigenvalue and associated eigenvectors of the reduced Jacobian matrix. Derivative of highest singular value of the inverse Jacobian matrix was proposed as a voltage stability index in [34]. Jacobian matrix determinant was used to develop global voltage stability margin (GVSM) index by Nagendra *et al.* [35]. Global voltage stability condition can be determined on the basis of this index. Voltage stability margin was computed on the basis of left eigen vector in [36]. In [37], it was described that diagonal elements ($\partial Q_i/\partial V_i$ and $\partial P_i/\partial \delta i$) of Jacobian matrix decreases with rise in loading of the system. It was proposed that the value of these elements can be used as voltage stability indicator. The drawback of the Jacobian matrix based indices is that they can assess global voltage stability but location (i.e. weak buses or lines of the system) cannot be identified. Moreover, due to high computational time, they are not suitable for online assessment of voltage stability [38].

On the other hand, bus / line voltage stability indices quickly estimate the voltage stability state. These indices use system parameters (i.e. bus voltages , power flow etc.) to determine weak buses / lines of the power system. These indices can be bifurcated as bus voltage stability indices and line voltage stability indices. Voltage stability state of the system is presented in the form of a scalar value by these indices. Voltage instability phenomenon initiates from the weak buses and quickly spreads to other buses of the system. To circumvent the cascading events, weak buses of the system must be identified. Bus voltage stability indices serve to identify the voltage weak buses of the system. The value of these indices varies between a specified limit from no load condition to maximum loading point. The bus whose index value is corresponding to maximum loading point, is considered as weak bus of the system.

A variety of of bus voltage stability indices have been proposed in the literature. L-index was proposed by Kessel *et al.* [48] to identify critical buses of the system using power flow solution. Scalar value of L-index varies changes from zero to one. Buses with lower value of L-index are termed as voltage stable buses. Conversely, the buses whose L-index is near to one, are termed as critical buses of the system. However, L-index shows erroneous results if load is different from constant power type load. In [49], Gu *et al.* developed an index to find crucial margin of all the buses of the system. However, wide-area measurement systems and accurate load modeling is required to identify the critical buses. Voltage collapse proximity indicator ($VCPI$) is proposed in [50] to determine the weak buses of the system. Index value is one for voltage stable bus whereas near voltage collapse point, the index approaches infinity. Tangent vector information is used in [51] to find voltage-weak buses of the system. Voltage stability of the system can be enhanced by shedding the load of the buses which have high tangent vector component. Milosevic *et al.* [52] proposed an index to estimate voltage stability margin of the load. However, two bus equivalent model corresponding to each line is required to identify the critical buses. Chebbo *et al.* [53] developed an index which is based upon ratio of equivalent Thevenin's impedance to load impedance. However, the proposed index does not give satisfactory results for heavy reactive loading of the system. Voltage stability load bus index ($VSLI$) is proposed in [54]. Phasor voltage corresponding to no load condition is needed to find the value of $VSLI$. Practically, it is a difficult task since system topology decides the no load voltage of a bus. In [55], P–Q–V curve technique is discussed to measure voltage stability margin of a bus. Weak buses can be ranked in the order of severity on the basis of this index. A sequential iterative method was proposed by Prada *et al.* [56] to distinguish the healthy buses from critical buses. In. [57], Obadina *et al.* presented an index to detect critical buses which drive the system towards voltage collapse.

Stressed conditions of lines are a threat to the voltage stability of the system which can be assessed using line voltage stability indices. These indices [58]-[64] recognize critical lines so that they can be relieved from overloading condition and voltage stability of the system can be maintained.

In [65], an index known as stability factor was presented to identify the critical lines of the system. It is based upon the single line equivalent of the power system. This index has nonlinear characteristics near the critical zone; therefore accurate voltage stability state cannot be predicted using this index. In [66], a line stability index based on localized risk indices is presented to recognize weak lines. Line loadability index L_s, is reported in [67] to identify critical lines and corresponding loading margin. The index is derived using the discriminant of a voltage quadratic equation. Maximum loadability index (MLI) is presented in [68]. It measures the proximity of the voltage stability state of a line from maximum loading point. The index value varies from greater than one to one as loading is increased from no load to maximum load. However, the indices [67] and [68] are more appropriate for radial distribution network. In [69]-[70], Quintela *et al.* [69] presented two line stability indices which are based on reactive and active power flow. Thevenin equivalent is not required in these indices. Out of them, one index is designed for transmission system while other one is intended for distribution system. Extended Line Stability Index ($ELSI$) was proposed by Wenyuan *et al.* [71] for finding the weak lines of a system. $ELSI$ of a line must be greater than one for voltage stable state. Musirin *et al.* [72] presented Fast Voltage Stability Index ($FVSI$) to identify the critical lines ranking the line contingencies in the order of severity. Moghavvemi *et al.* [65] developed stability factor L_{mn} to discover the stressed condition of the lines. Line stability factor $LQP$is presented by Mohamed *et al.* [73] to identify the critical state of lines. Index D_v is proposed by Ancheng *et al.* [74] which is computed on the basis of sensitivity of voltage w.r.t. power. Value of D_v index changes from 0.7 to 1 as load on the system is increased from no load to maximum load.

2.3.1 Critical Review Based on Indices

From the literature survey it is found that, there have been numerous static voltage stability indices which specify stability of the system globally or locally. However, global indices specify the stability of whole system, but unable to indicate weak region. On the other hand, principle concern of local indices is on the voltage stability of buses. The indices suggested in literature have ignored the line resistance and shunt branch parameters. It may lead to erroneous assessment of voltage stability of the system. Moreover, most of the voltage stability indices are complex; they require many parameters to assess voltage stability. Majority of these indices are not mapped to measure voltage stability margin.

Beside this, majority of the indices fail to prove that at maximum loading point, load impedance is equal to Thevenin's impedance at the corresponding load terminal. Moreover, most of these indices are not mapped to find the MVA margin of the system. Thus there is a scope of research in the area of voltage stability assessment methods. Therefore, there is a pressing need to develop a novel line stability index which can accurately assess the stressed condition of lines in advance so that proper control action can be initiated timely.

The voltage collapse phenomenon can be related to the action of tap changers on transformers, reactive power limiting protection at generators and load characteristics at low voltage magnitudes. At any point, where a change of voltage level is required, OLTC must be applied. Such OLTCs are usually built with fixed turn-ratios, or sometimes they are equipped with tap terminals for turn-ratio control. Tap changers are needed for such a control, which results in voltage change. OLTCs enable voltage regulation and/or phase shifting by varying the transformer ratio under load without interruption. Brief literature survey related to identification of critical OLTC and their modeling is presented in following section.

2.4 OLTC Literature Survey

Present power systems are operated under stressed condition. A slight disturbance at this stage results in reduction in EHV level voltages which is reflected finally in the distribution system network. The action of on-load tap changer helps to restore the voltage at previous levels. With each tap changing operation, the line current would increase, thereby increasing the reactive power loss of the system. As a result the reactive power output of the generators increases gradually and generators may reach to their reactive power capability limit. Beyond that generator loses their capability to support the system voltages, thereby causing a problem of voltage instability. Therefore, operation of OLTCs is critical for voltage stability and line losses of the system [76]-[79].

Numerous studies have been carried out in this area. Liu *et al.* [80] remodeled the voltage collapse phenomenon by co-relating non-linear dynamic models of impedance loads, OLTCs and de-coupled reactive power-voltage relations. Abe *et al.* [81]-[82] investigated the effect of dynamic tap changer on voltage stability using eigenvalue analysis.

Even though the proposed methodologies in [80]-[82] are effective, the lack of co-ordination between tap changers may cause a problem when there are voltage violations. Medinac *et al.* [83] proposed an approach to model, analyze, and design of slow distributed voltage control schemes. However, large deviations of system variables which lead to voltage collapse were not considered. In [80], a stability region around the stable equilibrium is derived through a nonlinear analysis of the continuous model. Since, voltage collapse involves large deviations of system variables, the nonlinear stability techniques are used to analyze the dynamics. If the load demand becomes excessively heavy, the secondary voltage may become unstable. Ohtsuki *et al.* [84] and Lee *et al.* [85] discussed the reverse action that the secondary voltage of a transformer is pulled down when the tap position of on-load tap changer is raised to increase the secondary voltage. Hong *et al.* [86] formulated the model of OLTC governing the reverse actions associated with inappropriate tap controls. However, in [84]-[86] system wide LTC control coordination was not investigated. Furthermore, so many algorithms have been presented to obtain the optimal settings of tap changers. Bansilal *et al.* [87] proposed an expert system for alleviating voltage violations by applying switchable shunt reactive compensation and transformer tap settings. Use of OLTC for voltage regulation was reported in [88]-[90]. Thukaram *et al.* [91] examined the effects of the OLTC transformers on voltage stability and recognized critical OLTCs to avoid possibilities of voltage instability conditions. Devaraj *et al.* [92] presented an improved genetic algorithm (GA) approach for voltage stability enhancement by optimizing OLTC tap settings, generator excitation, and reactive power compensation provided by capacitor banks. In [93], the Quasi-oppositional Differential Evolution ($QODE$) is employed to decrease the active power loss, enhance the voltage profile and to improve voltage stability of the system using optimal settings of transformer taps, generator terminal voltages, and reactive power output of shunt VAR compensators. Yang *et al.* [94] used hybrid differential evolution (HDE) technique to determine tap settings of OLTC transformers to improve voltage stability of the system.

Once the critical transformer is identified, voltage stability problem can be sorted out by providing reactive power support using flexible ac transmission system (FACTS) devices. Numerous studies have been carried out in this area [95]-[97]. Many researchers have proposed different artificial intelligence (AI) techniques to coordinate OLTC operation with FACTS devices for voltage stability improvement [98]-[108]. These methods use iterative trial and error progress with large data sets which are comparatively time- consuming. Conversely, the Taguchi method (TM) [110] is an effective tuning method which is well defined, systematic and simple in steps. Taguchi works on orthogonal array (OA) which gives all possible combinations, such that the best solution lies within the combinations. Taguchi method (TM) has been applied successfully to optimization problems in power systems [111]-[115].

2.4.1 Critical Review Based on OLTC

From the literature survey it was found that voltage stability problem has become a major concern in planning and operation of today's power system as a result of stressed conditions. It is known that the following disturbances, on-load tap changers (OLTCs), act to restore the load bus voltage and thus restore the load power to near pre-disturbance level. But the operation of OLTCs has a significant influence on voltage stability. Many researchers have proposed different methods to coordinate OLTC operation with other devices for voltage stability improvement. However, very little work has been presented in the literature about critical OLTC identification. Therefore, it is necessary to develop a technique for identifying the critical transformers and monitoring the effect of OLTCs on voltage stability. After identification of critical transformer, voltage stability problem can be sorted out by the coordinated operation of OLTC and FACTS devices. Therefore, a suitable optimization strategy is required to find optimal tap ratio of OLTCs and optimal sizing of FACTS devices so as to improve voltage stability of the system.

2.5 Optimum Locations of DGs and FACTS Devices for mitigation of line congestion

The problem of congestion mitigation and voltage stability of the system can be enhanced by allocation of distributed generators (DG) and FACTS devices at appropriate locations [116]-[117]. However, chief concerns raised regularly by utility manufacturers is regarding the location and sizing of DGs and FACTS devices. A lot of methodologies have been suggested in literature for optimal allocation of DGs and FACTS devices to mitigate congestion and voltage stability improvement. A brief literature survey related to different techniques used for congestion mitigation and voltage stability improvement is presented below:

Reddy *et al.* [118] analyzed genetic algorithm (GA) for single and multi-objective optimization techniques to enhance congestion management in the deregulated system. TCSC (Thyristor-Controlled Series Capacitor) and SVC (Static Var Compensator) were the two FACTS devices, used for the analysis purpose. Song *et al.* [119] considered placement of various FACTS devices using different optimization techniques and considering security indices. FACTS devices were investigated under normal and line contingency condition. Rahimzadeh *et al.* [120] discussed the optimal placement of shunt and series FACTS device. The author used STATCOM as a shunt device and SSSC as a series model by applying neural based technique. With this model, the authors took into account the power losses taking place in the converter and produced the required PQ-Phasor that is suitable for power system steady state analysis. Kulkarni and Ghawghawe [121] suggested that the proper placement of a series FACTS device like TCSC can be used to decrease the power flows in heavily loaded transmission line, thereby enhancing the load-ability limit of transmission lines. It resulted in decrease in power losses thereby managing congestion.

Thangalakshmi *et al.* [122] proposed Hybrid Fish Bee Swarm Optimization technique that was used to manage congestion. Hybrid Fish Bee Swarm Optimization technique is based on two techniques. One is Fish School Search (FSS) technique and the second is Artificial Bee Colony (ABC) technique. The authors have applied this technique on IEEE-30 bus transmission system. Results of the proposed technique show reduction in congestion. Srivastav *et al.* [123] studied two market models, that is, bilateral and multilateral contracts. The authors used the FACTS devices for managing congestion. FACTS devices, TCSC and SVC were modeled as variable reactance for this purpose. Two cases were studied for TCSC. In the first case, TCSC was placed in inductive mode for congested lines, and in the second case, it was placed in capacitive mode for lightly loaded buses. The optimal placement of TCSC is decided by using trial and error method. SVC is placed at different buses. The placement of SVC was decided by observing the rate of improvement of minimization of deviations from transaction made by market participants. Ushasurendra *et al.* [124] applied TCSC in series with transmission line to reduce congestion. Line Utilization Factor (LUF) was used to obtain the level of congestion in the transmission line. A fuzzy logic controller was used to control the active power flow for managing congestion. The proposed technique was applied on Modified IEEE-14 bus system. Then, the results based on fuzzy logic were compared with the results obtained by sensitivity method. Result shows that fuzzy logic based technique can also be used as an alternative technique for congestion management.

Dhansekar *et al.* [125] proposed Particle Swarm Optimization (PSO) based technique for reducing congestion in the transmission lines. UPFC (Unified Power Flow Controller) was optimally placed with appropriate sizing. The technique was applied on 5-bus test system. Results show the reduction in congestion in transmission lines.

Karami *et al.* [126] proposed an optimal solution for the placement of STATCOM. Artificial intelligence optimization technique was used to improve the voltage stability, security and reduce the congestion in the transmission lines. Gitizadeh et al. [19] used Sequential Quadratic Programming (SQP) problem for judging static security margin to reduce congestion and, in a second step, the author simulated annealing method for optimizing the problem. Rajalakshmi *et al.* [127] explained that the proper placement of a FACTS device can increase the transmission capability of transmission lines. The authors have implemented a technique for proper location of FACTS device which is based on the performance index and reduction of total reactive power losses.

Yousefi *et al.* [128] proposed an approach for transmission line congestion management by using combination of demand response FACTS device. In this paper, the work was carried out in two steps. In the first step, GENCOs bid the market for their maximum profit and clear ISO for the market based social welfare maximization. In the second step, network constraints, those related with congestion management, were included for market clearing procedure. A mixed integer optimization technique was used in the second step. In this step, demand response and FACTS devices were optimally coordinated with conventional generator.

Esmaili *et al.* [129] suggested a multi-objective congestion management technique. The author has optimized three objective functions (operating cost, voltage, and stability margin). The proposed technique efficiently placed and sized series FACTS devices on the congested transmission line by priority listing using LMP (Locational Marginal Prices).

Recently, Taguchi method (TM) has been extensively applied to solve many optimization problems in electric power system [110]-[115], because it can handle discrete variables easily and also manages continuous variables, nonlinear objective, and constraint functions [130]. TM is a statistical method, also known as robust design methods which are based on the design of orthogonal arrays (OA) to improve the performance of system. The development of TM is mostly attributed to the work of Genichi Taguchi [110]. The method does not need to use complicated algorithms and complex programming beside the software tool used for system modeling [131].

2.5.1 Critical Review Based on Congestion Management

From the literature survey it was found that congestion management plays a crucial role in the operational phase of present power system. Many researchers have suggested different methods to find optimal allocation of DG. Though, use of DGs for the congestion management has not been given proper attention. Congestion of lines also leads to voltage instability which can be mitigated by placing FACTS controllers of optimal sizing at voltage-weak buses. Many algorithms [132]-[146] have been suggested in the literature for optimal placement of FACTS controllers. However, the optimal coordination of DGs and STATCOMs is still a promising area of research. Therefore there is need to investigate the effects of placement of DG and FACTS devices for line congestion and voltage stability enhancement under heavy loading conditions.

2.6 Research Objectives

In the light of above discussion, it seems that analysis of voltage stability and congestion management is an effective area of research, and there is adequate scope to extend the existing research activities in this field for enhancing the performance of power systems.

Based on the above critical reviews, following objectives have been formulated to carry out the research work:

1. To carry out literature survey regarding voltage stability and its various aspects.
2. To investigate and compare the effectiveness of existing voltage stability indices.
3. To develop a new voltage stability index to assess the voltage stability of the system.
4. To determine weak lines of power systems using developed index and validate the results on the basis of standard techniques.
5. To examine the role of on-load tap changing transformer on voltage stability.
6. To develop an index to identify the critical transformer.
7. To examine the effect of DG and FACTS devices integration on voltage stability and line congestion.
8. To develop a suitable technique for optimal coordination of OLTC operation with FACTS controllers.

2.7 Structure of Dissertation

This dissertation is distributed into six chapters; this chapter comprises the research work carried out in this dissertation with description of the research motivation.

Chapter 2 deals with the comprehensive literature survey of the existing voltage stability indices and their limitations, critical transformer detection techniques, and optimal placement of DGs and FACTS devices along with the limitations of the existing methods. Finally, the research objectives are framed on the basis of research gaps found in literature survey.

Chapter 3 presents the formulation of new line voltage stability index for assessment of voltage stability. The chapter also investigates existing voltage stability indices under different operating conditions.

Chapter 4 presents a technique to detect critical transformer. A strategy regarding coordination of OLTCs with SVC has been also proposed for improving the voltage stability and decreasing the real power loss of the system.

Chapter 5 deals with congestion mitigation problem by optimal placement of DGs and FACTS devices.

Chapter 6 presents the conclusions of the research work along with the brief description of the future scope.

A full list of references used in the research is provided after the conclusions. The thesis ends with appendices which include detailed data tables and analysis relevant to the research.

Chapter 3

Voltage Stability Assessment Methods

With continuous rise in load demand the transmission network is operating under stressed conditions. Stressed condition of the line is a threat to voltage stability of the system. Therefore, voltage state of stressed line must be monitored continuously to avoid the risk of voltage collapse. Voltage stability condition can be assessed using a line stability index. Considering the need of power system, in this chapter, research work based upon assessment methods of voltage stability is presented. A novel line stability index has been developed to monitor the peril condition of the lines. The proposed index has been tested on standard IEEE 30 and 118 bus systems.

3.1 Introduction

It is essential to find existing operating state of voltage stability and distance with collapse point. Numerous analytical tools are available in the literature to measure voltage ability margin (VSM) and point of collapse (PoC) of the present operating state. Conventionally, P–V, Q–V curves and continuation power flow (CPF) were used to identify the problem of voltage instability [5] . However, these methods are time consuming and are not appropriate for real-time operation of power systems. This has led to the development of voltage stability indices for fast assessment of PoC. These indices are broadly used in identification of maximum permissible loading and relative voltage stability assessment. The indices present operating state of voltage stability in the form of a scalar quantity. Various types of indices have been discussed in literature in detail. Stressed condition of lines is a major reason of voltage instability which can be monitored on the basis of line voltage stability indices. A brief discussion of existing line voltage stability indices is presented below to appreciate the proposed index:

3.2 Existing Line Voltage Stability Indices

Existing line voltage stability indices compute the index value of different lines on the basis of various parameters. Value of index varies within a limit. The limits are corresponding to maximum and minimum voltage stability margin. If index value of a line is corresponding to minimum voltage stability margin, the line is considered critical and requires immediate control/remedial action. In order to understand the basics of these indices, some common indices related to voltage stability [65], [72], [73] have been briefly discussed in following section:

3.2.1 Line Stability Index (L_{mn})

The stability index L_{mn} presented by [65] is based on the power flow in the line. It measures voltage stability for each line. Higher value of L_{mn} of a line is an indication of closeness to the instability. The root discriminant of voltage quadratic equation is set equal to zero, to acquire real roots of voltage at the receiving end. If the discriminant is less than zero, the resultant roots will be imaginary which points towards voltage instability.

The stability index for this model [65] is represented as:

$$L_{mn} = \frac{4XQ_R}{V_S sin(\theta - \delta)^2} \tag{3.1}$$

Where, θ denotes impedance angle of line and δ is phase angle difference of sending and receiving end voltages. Index varies between 0 and 1. Closeness of index L_{mn} index to unity implies critical state of the line. To sustain secure condition, the index must be less than 1.

3.2.2 Fast Voltage Stability Index

Musirin *et al.* [72] derived Fast Voltage Stability Index ($FVSI$) to show voltage stability margin of a line. For a typical transmission line, the index is:

$$FVSI = \frac{4Z^2 Q_R}{V_S^2 X} \tag{3.2}$$

The line, whose index is near to one, will be the utmost stressed line. $FVSI$ index determines voltage weak lines of the network. The index [72] value changes from 0 to 1 as load on the system is increased from no load to maximum loading point.

3.2.3 Line Stability Factor *(LQP)*

The line stability factor proposed by Mohammed *et al.* [73] can be depicted as:

$$LQP = \frac{4X}{V_S^2}\left[\frac{XP_S^2}{V_S^2} + Q_R\right] \tag{3.3}$$

Where, V_S and P_S are sending end voltage and active power respectively, X is line reactance, and Q_R represents receiving end reactive power.

Index LQP varies between zero and one from no load condition to the voltage collapse point.

3.2.4 D_v Index

The proposed index D_v is proposed by Ancheng *et al.* [74] which is computed by utilizing voltage to power sensitivity. The stability index D_v can be presented as follows:

$$D_v = \frac{V_s}{\sqrt{2V_j^2 + 2(P_j'R + Q_j'X)}} \tag{3.4}$$

Where, V_i and V_j are sending and receiving end voltages respectively, and P_j' and Q_j' represents active and reactive powers at the buses i and j respectively. Line resistance and reactance are represented by R and X respectively. Closeness of D_v index to unity implies critical state of that line. Value of D_v index changes from 0.7 to 1 as load on the system is increased from no load to maximum load.

3.3 Formulation of New Index

Considering limitations of existing voltage stability indices, a new Line Voltage Stability Index ($LVSI$) is proposed to assess the voltage stability of power systems. The proposed index is derived from a voltage quadratic equation to acquire real roots of voltage. The proposed index is based upon ABCD parameters of transmission line which include line charging capacitance and resistance of line that were neglected by others voltage stability indices. Therefore, the proposed index assesses the voltage sensitivity precisely under all conditions and indicates the closeness of the system to voltage collapse point. The sending end voltage/current of a line can be related to receiving end voltage/current using $ABCD$ parameters in following way:

$$\begin{bmatrix} \overrightarrow{V_S} \\ \overrightarrow{I_S} \end{bmatrix} = \begin{bmatrix} \overrightarrow{A} & \overrightarrow{B} \\ \overrightarrow{C} & \overrightarrow{D} \end{bmatrix} \begin{bmatrix} \overrightarrow{V_R} \\ \overrightarrow{I_R} \end{bmatrix} \tag{3.5}$$

The terms $\overrightarrow{A}$, $\overrightarrow{B}$, $\overrightarrow{C}$, $\overrightarrow{D}$ are known as the transmission line parameters. The terms with arrow $\longrightarrow$ indicates phasor quantities while terms in normal letters represents scalar magnitudes. Parameters $\overrightarrow{A}$, $\overrightarrow{B}$, $\overrightarrow{C}$, $\overrightarrow{D}$ can be expressed as:

$$\overrightarrow{A} = 1 + \overrightarrow{Y} * \overrightarrow{Z/2} \tag{3.6}$$

$$\overrightarrow{B} = \overrightarrow{Z} \tag{3.7}$$

$$\overrightarrow{C} = \overrightarrow{Y} * (1 + \overrightarrow{Y} * \overrightarrow{Z}/4) \tag{3.8}$$

$$\overrightarrow{D} = \overrightarrow{A} \tag{3.9}$$

Receiving end active power can be expressed in terms of $ABCD$ parameters as follows [151]

$$P_R = \frac{|V_S||V_R|cos(\beta - \delta)}{|B|} - \frac{|A||V_R|^2 cos(\beta - \alpha)}{|B|} \tag{3.10}$$

Eq. 3.10 , is rearranged to form a quadratic equation of voltage in the following way:

$$|V_R|^2 - \frac{|V_S||V_R|cos(\beta - \delta)}{|A|cos(\beta - \alpha)} + \frac{P_R|B|}{|A|cos(\beta - \alpha)} \tag{3.11}$$

The sensitivity of voltage with respect to real power can be obtained from Eq. 3.11

$$\frac{dV_R}{dP_R} = \frac{-|B|}{2|V_R||A|cos(\beta - \alpha) - |V_S|cos(\beta - \delta)} \tag{3.12}$$

For the system to remain voltage stable the sensitivity must be negative.

$$\frac{-|B|}{2|V_R||A|cos(\beta - \alpha) - |V_S|cos(\beta - \delta)} < 0 \tag{3.13}$$

$$|V_S|cos(\beta - \delta) - 2|V_R||A|cos(\beta - \alpha) < 0 \tag{3.14}$$

On the basis of Eq. 3.14 it is concluded that the following condition must be satisfied to avoid voltage collapse of the system:

$$\frac{2|V_R||A|cos(\beta - \alpha)}{|V_S|cos(\beta - \delta)} > 1 \tag{3.15}$$

The proposed Line Voltage Stability Index ($LVSI_j$) can be defined on the basis of Eq. 3.15 as

$$(LVSI)_j = \frac{2|V_R||A|cos(\beta - \alpha)}{|V_S|cos(\beta - \delta_{SR})} \qquad \forall\ j = 1, 2, 3, ...l \tag{3.16}$$

Where, $LVSI_j$ indicates the index value for j^{th} line, it is a measure of local voltage stability. The global voltage stability of the system as shown in Fig. 3.1 can be found in following way:

$$(LVSI) = max(LVSI^1, LVSI^2, ..., LVSI^l) \tag{3.17}$$

Where, l is total no. of lines in the system.

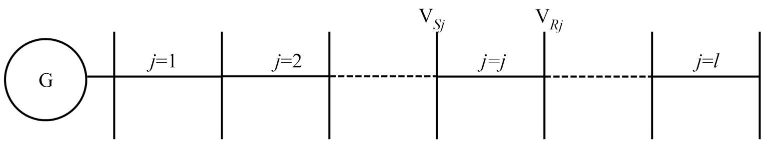


FIGURE 3.1: Generalized representation of transmission network.

To avoid the voltage collapse of the system the proposed index must be greater than unity, i.e.

$$LVSI > 1 \tag{3.18}$$

The proposed index value is near to 2 under normal load condition when system has large voltage stability margin. As line loading increases the value of index $LVSI_j$ of different lines decreases which shows the reduced voltage stability margin. If loading of a line is corresponding to maximum loading point, the index value of the line approaches unity that indicates critical state of the line. On the basis of index $LVSI_j$, the critical lines can be identified. The distance of proposed index with unity determines the voltage stability margin. The advantage of the proposed approach is that indices of different lines are computed simultaneously therefore, time consuming repeated power flow for each line is not required. The proposed index is very simple and requires only the data of voltage phasors of the buses which can be obtained through PMUs. The results obtained by computational procedure from observed are accurate and helps the system operator in fast decision making so that preventive control action may be applied in time. The flowchart for implementation of proposed algorithm is shown in Fig. 3.2. Here λ represents base load multiplication factor and λ_{max} represents maximum loadability factor. The sample 2-bus and 3-bus equivalent system, and standard IEEE 30 and 118 bus systems are considered to test the proposed index.

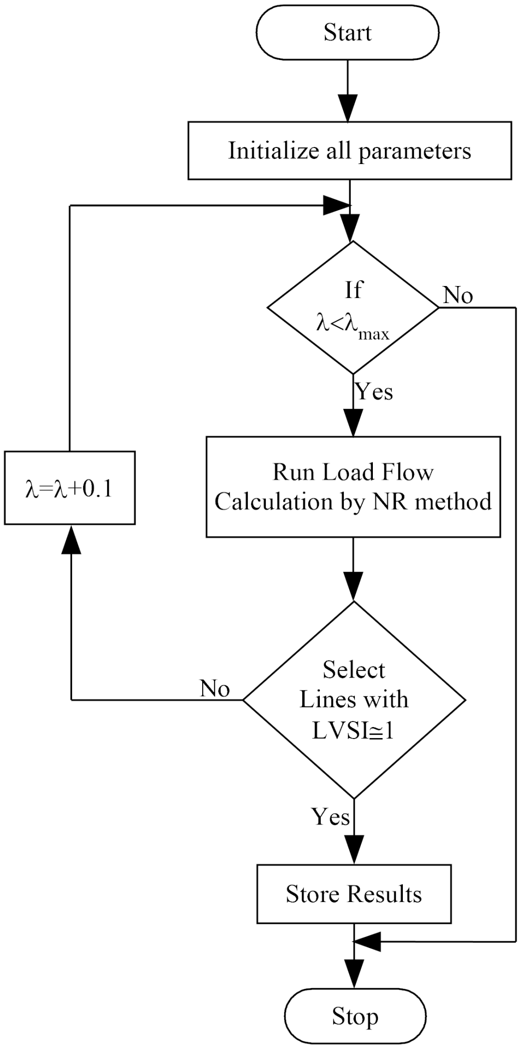


FIGURE 3.2: Flowchart of proposed index

3.4 Example to Illustrate the Proposed Index

In the beginning, the features of proposed index are investigated for a fundamental branch model. Then the study is extended for three bus system by assuming a new bus in the middle of the line. The simulation results of study for two and three buses are presented below:

3.4.1 Two-bus system

A fundamental branch model is shown in Fig. 3.3. The impedance of line is 0.05+j0.10 p.u. on 330 kV, 100 MVA base. The sending end voltage is p.u. and load at base case is $0.5 + j0.1$ p.u. [152]

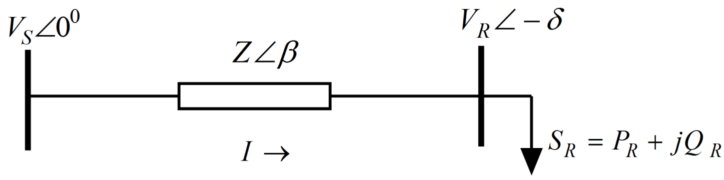


FIGURE 3.3: Fundamental two bus system

Index value is computed for different loading conditions. Load is varied from base load to maximum loading point. Two cases are considered for simulation; 1) variation of apparent power at constant power factor, 2) variation of reactive power. The case study is presented below:

Case 1: Active and reactive power increment at constant power factor

In this case the apparent loading of system is increased by a factor λ. Index $LVSI$ is computed for different loading scenarios and compared with well-established indices LQP, L_{mn}, $FVSI$ and D_v as shown in Table 3.1. The value of proposed index varies from 2 to 1 from no load to maximum loading point; conversely the values of indices LQP, L_{mn} and $FVSI$ varies between $0-1$ and D_v [74] index vary from $0.7-1$ for the same case. Near to maximum loading, the value of proposed index is 1.0020 which envisages the voltage collapse point. Above this loading the receiving end bus of the line will be voltage unstable. Therefore, the receiving end bus of the line is considered as weak bus of the system. The results are also supported by indices L_{mn} [65], and D_v [74] whose value are also approaching unity.

Maximum loading indicated by the proposed method is also confirmed by comparing equivalent load impedance with the transmission impedance for the same operating point. At maximum loading point the Thevenin impedance of the line (Z_{TR}) must be equal to equivalent load impedance [$Z_L = V_R^2/(S_R)^*$]. As shown in Table 3.1, for a loading factor 2, Z_{TR} and Z_L are 0.1118 p.u. and 0.1122 p.u. respectively which confirms that current operating point is near to maximum loading point. Slightly above this loading, voltage of the system collapse. Value of proposed index is 1.0020 at this point which substantiate the fact that proposed index is a measure of voltage stability state of the system in numerical terms.

TABLE 3.1: Simulation results for two-bus system while increasing both active and reactive load

Loading Factor λ	V_S (p.u.)	V_R (p.u.)	LQP [73]	L_{mn} [65]	$FVSI$ [72]	D_v [74]	Proposed index	Z_{TR} (p.u.)	Z_L (p.u.)
0	1	1	0.0263	0.0263	0.021	0.7071	1.9999	0.1118	0.8944
1	1	0.854	0.5	0.5	0.39	0.765	1.7071	0.1118	0.6554
1.2945	1	0.797	0.6472	0.6472	0.501	0.792	1.5939	0.1118	0.4422
1.4651	1	0.759	0.7326	0.7325	0.5646	0.8115	1.5172	0.1118	0.3545
1.6888	1	0.697	0.8444	0.8444	0.647	0.847	1.3945	0.1118	0.2595
1.9091	1	0.607	0.9545	0.9545	0.7272	0.9075	1.2132	0.1118	0.1749
2 (Max loading point)	1	0.501	0.9993	1	0.76	0.999	1.002	0.1118	0.1122

Case 2: Reactive loading increment, keeping active power constant

Voltage stability of the system is associated with reactive power demand of the load. Therefore, features of proposed index are also investigated for diverse reactive loading conditions. Variation of proposed index with reactive loading is presented in Table 3.2. The results in the table show that index value consistently decreases towards unity with increase in reactive loading. The proposed index becomes 1.0265 at maximum loading point that indicates closeness of operating state to voltage collapse point. Above this loading, load flow diverges. At this stage, value of the indices $FVSI$ and D_v [74] are 0.8353 and 0.9110 which point towards availability of loading margin.

TABLE 3.2: Simulation results for two-bus system while increasing reactive load

Loading Factor λ	$V_S(p.u.)$	$V_R(p.u.)$	LQP[73]	L_{mn}[65]	$FVSI$[72]	D_v[74]	Proposed index
0	1	0.973	0.014	0.0132	0.001	0.7001	1.8662
1	1	0.854	0.5	0.5	0.39	0.765	1.7071
1.3412	1	0.801	0.6854	0.6706	0.5265	0.7902	1.5372
1.5284	1	0.768	0.7921	0.7642	0.6014	0.807	1.4375
1.7451	1	0.723	0.9219	0.8725	0.688	0.832	1.3116
2	1	0.652	1.088	1	0.79	0.8769	1.1333
2.1132 (Max loading point)	1	0.605	1.0712	1	0.8353	0.911	1.0265

3.4.2 Three bus system

To show that the features of proposed index are unperturbed by change of topology; a third bus is introduced in the middle of existing buses as shown in Fig. 3.4. The line is subdivided in two equal parts i.e. line-1 and line-2. The load at buses 2 and 3 are $0 + j0$ p.u. and $0.5 + j0.1$ p.u. respectively at base case. The index is computed for both of the lines for different loading conditions as shown in Table 3.3. The proposed index of line-2 reaches to 1.0049 for a MVA loading 2 p.u. It shows that receiving end bus 3 of line-2 is near to voltage instability; therefore loading of line-2 is not permitted above this limit. The same maximum loading was obtained for 2 bus system. It shows that characteristics of the proposed index are unaffected by the change of topology of the system. Although the index value 1.3352 of line-1 for this loading indicates that receiving end bus no 2 of line-1 is still voltage stable, therefore line-1 can be loaded beyond this limit provided the increased load does not pass through line-2. When a load is connected at bus no 2, both of the lines can have different maximum loading. The maximum loading point of each line is indicated by their respective line index $LVSI_j$.

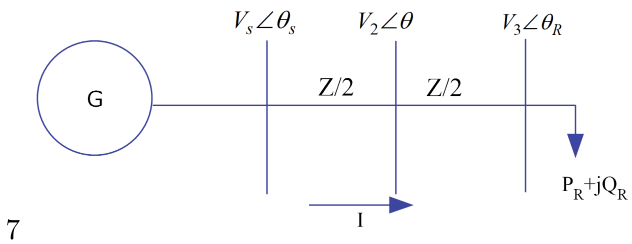


FIGURE 3.4: One line diagram of three bus system

Table 3.3: Simulation results for three bus system while increasing MVA load

Loading Factor λ	$V_1(p.u.)$	V_2 (p.u.)	$V_3(p.u.)$	LQP[73]	L_{mn}[65]	$FVSI$[72]	D_v[74]	Proposed $LVSI_j$ for line 1	Proposed $LVSI_j$ for line 2	$Z_{TR}(p.u.)$	Z_L (p.u.)
1	1	0.927	0.854	0.2295	0.2911	0.2911	0.7364	1.8536	1.842	0.1118	0.6554
1.2945	1	0.898	0.797	0.3143	0.4009	0.4009	0.7506	1.797	1.774	0.1118	0.4422
1.4651	1	0.879	0.759	0.37	0.4737	0.4737	0.7606	1.7586	1.7254	0.1118	0.3545
1.6888	1	0.849	0.697	0.4563	0.5863	0.5863	0.7806	1.6972	1.6432	0.1118	0.2595
1.9091	1	0.803	0.607	0.5698	0.7396	0.7396	0.813	1.6066	1.5103	0.1118	0.1749
2	1	0.668	0.335	0.76	1	1	0.9697	1.3352	1.0049	0.1118	0.1122

3.4.3 Reverse power flow of two bus system

The proposed index is also validated for reverse power flow condition. Two cases have been considered;

1) P<0, Q>0; 2) P>0, Q<0.

Case 1: P= -0.5 p.u., Q=1 p.u.

Case 2: P= 0.5 p.u., Q= -1 p.u.

Total load is increased until the power flow diverges. The results for case 1 and 2 are shown in Table 3.3 and 3.5 respectively. For case 1, the proposed index is 1.0393 at maximum loading point which indicates the critical voltage stability state of the system. It is seen from Table 3.4, that value 1.4303 of LQP index shows voltage collapsed state, whereas indices $FVSI$ and D_v indicate stable voltage stability state. Therefore, these indices interpret false state of voltage stability. From Table 3.5, it is observed that for case 2, near maximum loading, the proposed index value is 1.0392 that proves its ability to indicate maximum loading point. However, indices L_{mn} and $FVSI$ fails to identify the critical state. Index LQP again incorrectly shows voltage collapsed state. Although in this case, index D_v is able to detect the voltage unstable condition. The consistency of results under all the possible conditions validate the proposed index whereas other indices fail to identify the voltage collapse point for some of the cases.

Table 3.4: Proposed index for 2-bus system when P<0 and Q>0 (Case-1)

Loading Factor λ	$V_S(p.u.)$	$V_R(p.u.)$	LQP [73]	L_{mn} [65]	$FVSI$ [72]	D_v [74]	Proposed index $LVSI$
1	1	0.912	0.5669	0.5	0.39	0.7425	1.5028
1.2945	1	0.879	0.7724	0.6472	0.501	0.7582	1.3688
1.4651	1	0.857	0.9048	0.7325	0.5646	0.7695	1.2916
1.6888	1	0.825	1.099	0.8444	0.647	0.7869	1.1893
1.9091	1	0.789	1.3235	0.9545	0.7272	0.808	1.0846
2	1	0.771	1.4303	1	0.76	0.8195	1.0393

TABLE 3.5: Proposed index for 2-bus system when P>0 and Q<0 (Case-2)

Loading Factor λ	$V_S(p.u.)$	$V_R(p.u.)$	LQP [73]	L_{mn} [65]	$FVSI$ [72]	D_v [74]	Proposed index $LVSI$
1	1	1.066	0.4351	0.3916	0.3038	0.7837	1.5857
1.2945	1	1.083	0.5469	0.4761	0.3651	0.8059	1.4997
2.5651	1	1.143	0.9965	0.7409	0.5329	0.8501	1.2295
2.888	1	1.156	1.1093	0.7889	0.5557	0.8656	1.1788
3.1991	1	1.167	1.2196	0.8294	0.5713	0.9465	1.1348
4	1	1.194	1.5187	0.9112	0.585	1.0001	1.0392

3.5 Simulation Results on Standard Test Systems

The performance of the proposed index is also tested on IEEE 30-bus and IEEE 118 bus standard test systems [153] under various operating conditions and compared with the well-established LQP [73], L_{mn} [65], $FVSI$ [72] and D_v [74] indices to validate its practicability. A computer software program has been developed in the MATLAB environment to perform the simulation. A convergence tolerance of 10^{-12} p.u. has been set for maximum power mismatch. The $LVSI_j$ index for different lines is computed under various operating and system conditions. The proposed index value is near to 2, for no load conditions. The value of proposed index decreases with increase in line loading while value of other indices i.e.LQP [73], L_{mn} [65] , $FVSI$ [72] increases from zero towards unity and value of D_v index varies between $0.7 - 1$. Above this loading voltage collapse occurs. When the system is close to voltage collapse; the proposed index approaches unity. Lines whose index value is near to unity are termed as critical lines. Proposed index is tested under following operating and system conditions:

a) Base case loading.

b) Increased reactive power loading.

c) Increased active power loading.

d) Increased MVA loading.

e) Contingency condition.

Moreover, the index is also mapped to measure the MVA margin of the system. The test results for various operating system conditions are presented in following sub-sections:

3.5.1 Base Case

The proposed index is computed at base case for all the branches of standard test systems using results of load flow and compared with other voltage stability indices; L_{mn}, $FVSI$, LQP, and D_v. The results of simulations are presented below:

A. Base case loading for IEEE 30-bus system

IEEE 30-bus system has 6 generator buses, 24 load buses, and 41 lines. Test results for IEEE 30- bus at base case are shown in Table 3.6. It is noticeable from this table that at base case, value of indices L_{mn} [65], LQP [73], and $FVSI$ [72] of different lines are near to zero whereas D_v index [74] value is close to 0.7. Proposed index is around 1.9 for this case. It shows that all the lines are in secure state and system is voltage stable for base case.

B. Base case loading for IEEE 118-bus system

The proposed index is also tested on IEEE 118-bus to prove its adaptability on larger system, the results are shown in Table 3.7. The index L_{mn} [65] for line 87-86 is equal to 0.0958 at base case. Indices [72]-[73] also have almost same value which indicates the voltage stable state of the lines. For the same case, the proposed index is equal to 1.9913 which is an indicator of secured state of voltage stability.

TABLE 3.6: Line indices for IEEE 30-bus system at base case loading

Line (From-to)	LQP [73]	L_{mn} [65]	$FVSI$ [72]	D_v [74]	Proposed Index
6-28	0.0221	0.0245	0.0244	0.7071	1.9243
7-5	0.0544	0.0653	0.0641	0.7144	1.8853
12-16	0.0252	0.0303	0.03	0.7201	1.9824
16-17	0.0105	0.0123	0.0122	0.7015	1.9858
10-20	0.0342	0.0337	0.0294	0.7192	1.9661
20-19	0.007	0.0087	0.0087	0.703	1.9939
25-24	0.02	0.0268	0.0266	0.7099	1.9704
27-29	0.0359	0.035	0.03	0.7281	1.9607
27-30	0.0541	0.0519	0.048	0.7048	1.9308
29-30	0.0144	0.0142	0.0123	0.7194	1.9663

TABLE 3.7: Line indices for IEEE 118-bus system at base case loading

Line (From-to)	LQP [73]	L_{mn} [65]	$FVSI$ [72]	D_v [74]	Proposed Index
2-1	0.0536	0.0533	0.0495	0.726	1.9764
5-4	0.0252	0.0252	0.0242	0.7153	1.9575
37-34	0.01	0.01	0.0097	0.7124	1.9441
39-40	0.0096	0.0096	0.0088	0.7112	1.9905
56-55	0.004	0.004	0.0037	0.7093	1.9837
67-62	0.0602	0.0595	0.0601	0.731	1.8352
69-70	0.0845	0.0816	0.099	0.7714	1.6389
87-86	0.0958	0.0957	0.0942	0.7398	1.9913
96-80	0.1261	0.1258	0.1211	0.7351	1.8852
97-80	0.1216	0.128	0.1215	0.7411	1.8582
98-80	0.0839	0.0834	0.0792	0.726	1.8578
105-106	0.0202	0.0202	0.0191	0.7002	1.9732
115-114	0.0035	0.0035	0.0034	0.708	1.9962

3.5.2 Heavy Reactive Loading

Heavy demand of reactive power is the root cause of voltage instability of the system. To investigate the effect of increased reactive demand on voltage stability, reactive loading of the system is increased near to the point of voltage collapse. The simulation results for IEEE 30-bus and IEEE 118-bus test systems are presented below to test the capability of the proposed index to detect voltage instability.

A. Reactive loading increment for IEEE 30-bus system

Reactive loading of a bus is raised to the level of voltage collapse point to investigate the impact of increased reactive power demand on proposed index. Simulation results for IEEE 30-bus system are summarized in Table 3.8. Proposed index is equal to 1.0135 for line 20-10 when reactive loading of bus-20 is corresponding to the maximum loading. Beyond this loading load flow does not converge. It shows the ability of the proposed to points the voltage unstable condition for heavy reactive loading condition. The result is validated by index D_v [74]. For the same case, other indices show that there is still stability margin in line 20-10 which gives an imprecise indication of voltage stability. For the same loading, indices of other lines are also shown in the table. Simulation results for increased reactive loading of other nodes also confirm the findings.

B. Reactive loading increment for IEEE 118-bus system

The efficacy of proposed index under heavy reactive loading is also investigated for larger IEEE 118-bus system. Reactive loading of a bus is raised up to the level of voltage collapse point. The proposed index is computed and compared with other indices LQP, L_{mn}, $FVSI$, and D_v. The result of comparison for IEEE 118-bus is shown in Table 3.9. When reactive loading of bus-11 is corresponding to maximum loading, value of proposed index becomes 1.0273 for line 11-4 which is an indicator of infinitesimal small voltage stability margin. For the same case, value of indices L_{mn}, $FVSI$ is higher than their critical value which is an erroneous indicator of lost state of voltage stability. While value 0.8525 for index D_v predicts availability of loading margin at the maximum loading point.

Table 3.8: Line indices for heavy reactive power loading of IEEE 30-bus system

Loading (p.u.)	Line from-to	LQP[73]	L_{mn} [65]	$FVSI$ [72]	D_v[74]	Proposed Index
Q=1.0248 p.u. at node 20	20-10	0.8452	0.7213	0.9045	0.9724	1.0135
	20-19	0.3647	0.3556	0.3228	0.7744	1.7172
	10-6	0.6588	0.3756	1.4300	0.7600	1.7548
	10-9	0.3007	0.3007	0.3001	0.7341	1.8099
Q=0.9905p.u. at node 23	23-15	1.2468	0.845	1.0525	0.9803	1.0291
	23-24	0.8918	0.9927	0.9784	0.8493	1.1321
	15-12	0.3965	0.4420	0.4337	0.7780	1.6322
	12-13	0.5490	0.5780	0.5793	0.7522	1.7696
Q= 0.3485 p.u. at node 30	30-27	1.1491	0.8588	1.0712	0.9814	1.0375
	30-29	0.7424	0.8335	0.6685	0.8145	1.3402
	28-27	0.5580	0.6101	0.5151	0.7970	1.4686

Table 3.9: Line indices for heavy reactive power loading of IEEE 118-bus system

Loading (p.u.)	Line from-to	LQP [73]	L_{mn} [65]	$FVSI$ [72]	D_v [74]	Proposed Index	Remarks
Q=17.2431 p.u. at node 11	11-4	0.9081	1.0245	1.0035	0.8525	1.0273	Critical
	11-5	0.8928	0.9957	0.9874	0.7239	1.0999	Critical
	11-13	0.3967	0.4423	0.4335	0.7702	1.6101	
Q=3.28 p.u. at node 51	51-49	0.8801	1.0267	1.0127	0.8199	1.0109	Critical
	51-58	0.7102	0.8658	0.8001	0.8086	1.2167	
	52-53	0.7469	0.8295	0.7934	0.8106	1.1571	
	53-54	0.5490	0.5780	0.5793	0.7600	1.6924	
	58-56	0.7123	0.8404	0.8039	0.7947	1.2982	
Q= 7.0 p.u. at node 96	96-97	0.7970	0.8584	0.8285	0.9387	1.0535	Critical
	96-94	0.7357	0.8214	0.8195	0.7272	1.4142	
	97-80	0.7086	0.7452	0.7366	0.7021	1.3422	
	96-82	0.7602	0.8797	0.8313	0.8951	1.1783	

3.5.3 Heavy Active Loading

A reliable index indicates the voltage stability state not only for heavy reactive loading but also for heavy active loading conditions. Therefore, the effectiveness of proposed index is investigated under heavy active loading. Results of simulation for IEEE 30 and 118 bus systems are presented below for analysis:

A. Active Loading Increment at IEEE 30- bus system

Effect of real power loading on proposed index is investigated by increasing loading at each bus till the point of voltage collapse. As shown in Table 3.10, the proposed index reaches near to unity at maximum loading point. Conversely, values of other indices [65] [72] [73] are far away from critical value which shows that these indices [65] [72] [73] fail to identify the point of voltage collapse. The critical lines are also identified on the basis of proposed index. As shown in the Table 3.10, bus 17 is loaded to the maximum loading point, the proposed index for line 1-3 decreased to 1.0097. It shows that line 1-3 is in a critical state and appropriate control action is required to curtail the loading in order to avoid voltage collapse. Conversely, index L_{mn} [65] and $FVSI$ [72] are far below unity and therefore unable to identify the critical state of line 1-3. The index LQP [73] value is 1.2863 which falsely indicates that voltage collapse had already occurred.

B. Active Loading Increment at IEEE 118- bus system

To prove the performance of index $LVSI$ under heavy active loading, the test is also performed on IEEE 118-bus system. The active load of a bus is raised until divergence of load flow occurs. The results are depicted in Table 3.11. These results support the results obtained for IEEE-30 bus test system.

3.5.4 Increased MVA Loading

Application potential of proposed index for MVA loading of the system is explored to prove its adaptability under diverse operating conditions. Analysis of results of standard IEEE bus systems are presented below:

TABLE 3.10: Line indices under heavy active loading for IEEE 30- bus system

Loading (p.u.)	Line from- to	L_{mn} [65]	$FVSI$ [72]	LQP [73]	D_v [74]	Proposed Index	Remarks
P= 5.43 at node 3	4-3	0.8452	0.7312	0.9045	0.9345	1.0291	Critical
	6-8	0.3647	0.355	0.3272	0.8116	1.589	
	2-6	0.6588	0.3765	1.4330	0.8571	1.2665	
	9-11	0.3007	0.3007	0.3007	0.8070	1.8363	
P= 5.8404 at node 5	6-7	0.1281	0.0841	0.7171	0.8389	1.0388	Critical
	2-6	0.2749	0.1884	0.7779	0.8231	1.1138	
	3-1	0.4637	0.4395	1.1526	0.8007	1.2311	
P= 2.23 at node 17	1-3	0.6057	0.6127	1.2863	0.8228	1.0097	Critical
	2-6	0.2633	0.1999	0.5851	0.8141	1.2283	
	10-17	0.7279	0.5384	0.9947	0.8131	1.4183	
	12-16	0.7971	0.6377	0.8449	0.8263	1.3753	

TABLE 3.11: LVSI index for 118-bus system under heavy active power loading

Load Bus	Loading (p.u.)	Critical Line	L_{mn} [65]	$FVSI$ [72]	LQP [73]	D_v [74]	Proposed Index
4	10.47	42-49	1.3806	1.2059	2.2468	0.9431	1.0451
13	5.032	13-15	0.24	0.2233	0.8698	0.9662	1.0066
14	6.132	69-70	0.2685	0.2156	0.5974	0.9812	1.0191
15	11.16	23-22	0.3961	0.3295	0.6713	0.9827	1.0222
16	5.825	69-70	0.1938	0.161	0.4541	0.9915	1.0692
18	10.62	66-49	0.1731	0.1512	0.3645	0.993	1.0197
19	9.225	25-27	0.2541	0.219	0.4881	0.9941	1.0077
20	3.672	20-21	0.6486	0.5409	0.9168	0.9914	1.0677
21	2.856	20-21	0.6486	0.5409	0.9168	0.9601	1.0677
27	10.044	70-69	0.9875	0.8713	1.807	0.9831	1.0236
109	6.096	104-100	1.188	1.041	2.0298	0.9608	1.0135
110	6.747	104-100	1.1668	1.0268	2.0042	0.9835	1.0247
112	5.3	104-100	1.1531	1.0175	1.9876	0.9831	1.0322
114	8.72	70-69	0.9676	0.8574	1.7831	0.9584	1.035
115	8.756	70-69	1.017	0.8917	1.842	0.9919	1.0075

A. MVA loading increment at IEEE 30- bus system

In this scenario, active and reactive power loading of all the buses is increased simultaneously till the point of convergence. As shown in Table 3.12, the proposed index value at this point is 1.0129 which indicates closeness to voltage collapse point. Other indices are far away from their critical value that shows their incompetency to detect the voltage unstable state. Line 27-30 is the most critical line for this case. It is evident from these results that proposed index is a versatile index which is competent to show unstable voltage state for all the possible conditions; i.e. active/ reactive as well as MVA loadings.

Table 3.12: LVSI index for IEEE 30-bus system for heavy MVA loading

Loading Factor	Line from-to	LQP [73]	L_{mn} [65]	$FVSI$ [72]	D_v [74]	Proposed Index	Remarks
2.65	27-30	0.6982	0.6678	0.5273	0.9764	1.0129	Critical
	2-6	0.7289	0.2646	0.1855	0.8971	1.1342	
	2-4	0.5911	0.3916	0.3182	0.8752	1.3568	
	7-5	0.2824	0.3554	0.3338	0.8046	1.5934	

B. MVA loading increment at IEEE 118 bus system

MVA loading of IEEE 118-bus is raised to 190% of base case. Above this loading load flow does not converge. The voltage stability indices are computed for this loading and are shown in Table 3.13. The proposed index is 1.0803 for line 47-46 which indicates that loading is critical and line 47-46 is likely to be collapse for further loading. Other indices are far below their critical values at this loading which shows their incompetency to predict voltage unstable state. The consistency of results validates the applicability of the proposed index.

Table 3.13: LVSI index for IEEE 118 bus system under MVA loading

Loading Factor	Critical Line	LQP [73]	L_{mn} [65]	$FVSI$ [72]	D_v [74]	Proposed Index
1.9	47-46	0.3815	0.6104	0.5136	0.8731	1.0803

3.5.5 Contingency Analysis

The contingency analysis of a system is essential to diagnose the effects of outage of transmission lines or transformers. The analysis aids in initiating essential control actions to uphold power system stability, reliability, and security. The power system security is generally based upon $(N-1)$ single contingency criterion. To investigate the efficacy of proposed index for envisaging voltage collapse during single branch outage, contingency analysis of IEEE 30 and 118 bus test systems is carried out for base case and predetermined loading conditions. Results and its analysis are presented in the following sections:

A. Contingency analysis of IEEE 30 bus system

A pre-determined load is selected as half the maximum reactive loading of the bus on the basis of [72]. Maximum reactive loading of the buses are computed using NR load flow. The load flow is run with single line outage and $LVSI$ index is measured from the solution of load flow and compared with other contemporary indices. The crucial lines are identified on the basis of $LVSI$, whose outage commences the process of voltage collapse. The receiving end buses of crucial lines are conceded as weak branches of the system. Different contingencies are ranked in Table 3.14 in descending order on the basis of proposed index. Contingency is considered as more severe if index value is near unity.

The outcomes of contingency analysis for buses $4, 15$, and 23 are presented in Table 3.14. Reactive loading of the buses were affixed to half of the maximum permissible reactive load. The reactive loads on other buses were retained equal to base loads. From Table 3.14, proposed index of branch 4-2 is observed to be 1.0561 for outage of branch 1-2, which shows that this contingency is critical. A slight disturbance around this loading causes voltage collapse. However, for the same case, value of other indices, particularly LQP [73] and $FVSI$ [72] indices are far below unity, which implies healthy voltage stable state. Thus proposed index is capable to monitor the extreme condition of lines during contingency which assists operator to take suitable measures to circumvent voltage collapse.

B. Contingency analysis of IEEE 118 bus system

To examine the practicality of the proposed index for visualizing the PoC during line outage, contingency analysis is performed on IEEE 118-bus system under pre-determined load. A pre-determined load on buses 11, 51, 96 is selected as half the maximum reactive loading of the bus on the basis of [72]. Maximum reactive loading of the bus is obtained from Table 3.9. The effects of contingency analysis for buses 11, 51, 96 are presented in Table 3.15.

TABLE 3.14: Contingency ranking for IEEE 30- bus system with pre-specified reactive load

Pre-specified reactive load:							
Q_4= 2.984p.u. , Q_{15}=0.841p.u. , Q_{23}=0.495p.u.							
Rank	Line Outage	Critical Line	LQP [73]	L_{mn} [65]	$FVSI$ [72]	D_v [74]	Proposed Index
1	1-2	4-2	0.9366	0.6913	0.7987	0.9202	1.0561
2	12-4	12-13	1.4181	0.6625	0.6046	0.813	1.1851
3	12-16	12-4	0.8086	0.8086	0.8086	0.8001	1.2378
4	15-12	25-24	0.7292	0.7298	0.7287	0.7905	1.346
5	3-1	2-6	0.6135	1.33	0.5775	0.7822	1.4353
6	6-7	23-15	0.2108	0.1121	0.0983	0.7751	1.5071

TABLE 3.15: Contingency ranking for IEEE 118- bus system with pre-specified reactive load

Pre-specified reactive load:							
Q_{11}= 8.62p.u. , Q_{51}=1.6400p.u. , Q_{96}=3.5p.u.							
Rank	Line Outage	Critical Line	LQP [73]	L_{mn} [65]	$FVSI$ [72]	D_v [74]	Proposed Index
1	4-11	25-27	0.9663	0.7014	0.7981	0.9507	1.0541
2	5-11	25-23	1.1481	0.6625	0.6046	0.8308	1.162
3	49-51	49-54	0.798	0.798	0.798	0.8105	1.3161
4	51-52	59-55	0.7491	0.7396	0.7387	0.7922	1.4298
5	80-96	85-83	0.6235	1.03	0.6775	0.7851	1.5702
6	82-96	89-92	0.2508	0.1211	0.0989	0.7651	1.6338

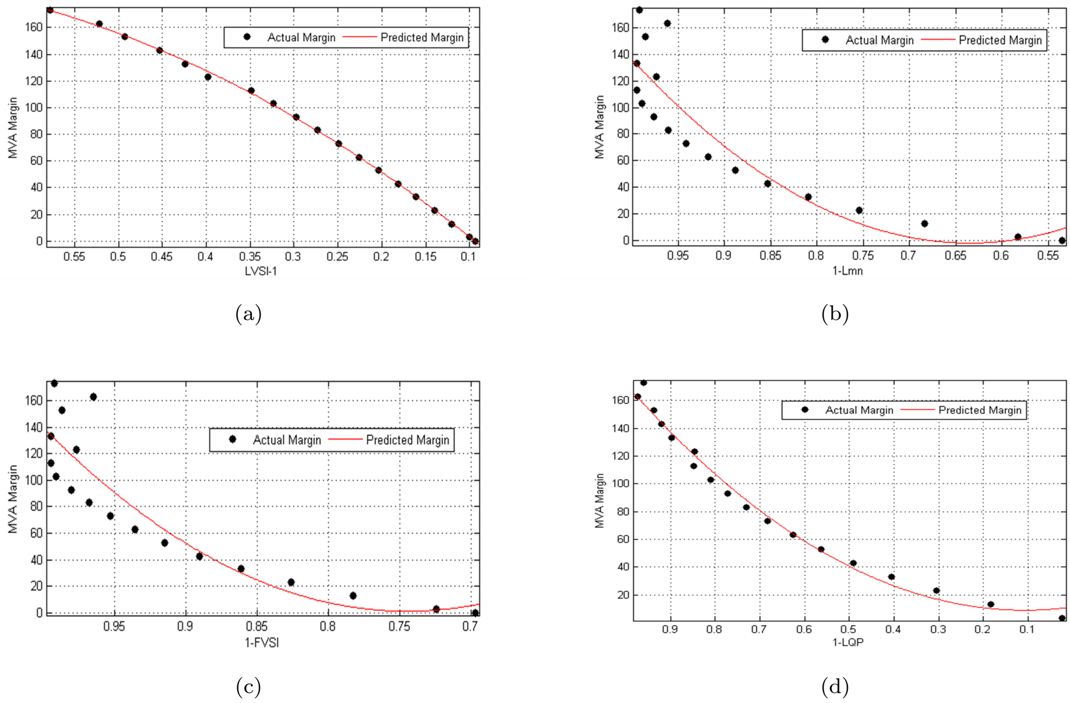
3.6 MVA Margin Estimation

An index will be useful for a system operator if it can provide the valuable information of available loading margin. Therefore, proposed index is mapped to measure the MVA margin of the system. The index value is 2 at no load where MVA margin is maximum. As loading increases, MVA margin and proposed index $LVSI$ decreases. At maximum loading point where loading margin is nil, the proposed index is 1. Therefore, $LVSI-1$ is a measure of loading margin of the system. A graphical relationship is developed between MVA margin and $LVSI-1$ to map the proposed index in terms of MVA loading margin. MVA margin is estimated for different loading conditions on IEEE 30 and 118 bus systems and compared with actual margin to verify the proposed methodology. The results of simulation are presented below:

A. Margin estimation of IEEE 30 bus system

The efficacy of proposed $LVSI$ in terms of MVA margin is investigated on IEEE 30 bus system at a given operating point. $LVSI$ varies between 2 to 1 as loading increases from no load to MLP. Thus, $LVSI-1$ is a source of estimation of MVA margin. The relationship is developed between MVA margin and $LVSI-1$ as depicted in Fig. 3.5 for IEEE 30-bus test system respectively. It has also been compared with actual margin which is shown by dots points. As shown in Fig. 3.5(a), for loading factor $\lambda = 1.7$, the actual loading margin is 103 MVA. For this loading index $LVSI$ is 1.3236. From Fig. 3.5(a), the estimated MVA margin for this value of index is also 103 MVA, which shows that

MVA margin can be estimated to high degree of accuracy using proposed index. For same loading, the MVA margin is also computed using indices L_{mn} [65], LQP [73], $FVSI$ [72] as shown in Figures 3.5(b)-3.5(d) and it is found to be 128.8 MVA, 130.4 MVA and 109.5 MVA respectively which are quite different from actual margin. It is to be noted down here that in other indices the margin is estimated by 1-Index, as their value varies from 0 to 1 from no load to MLP.



(a) (b) (c) (d)

FIGURE 3.5: MVA margin comparison for proposed index and other indices for IEEE 30-bus system

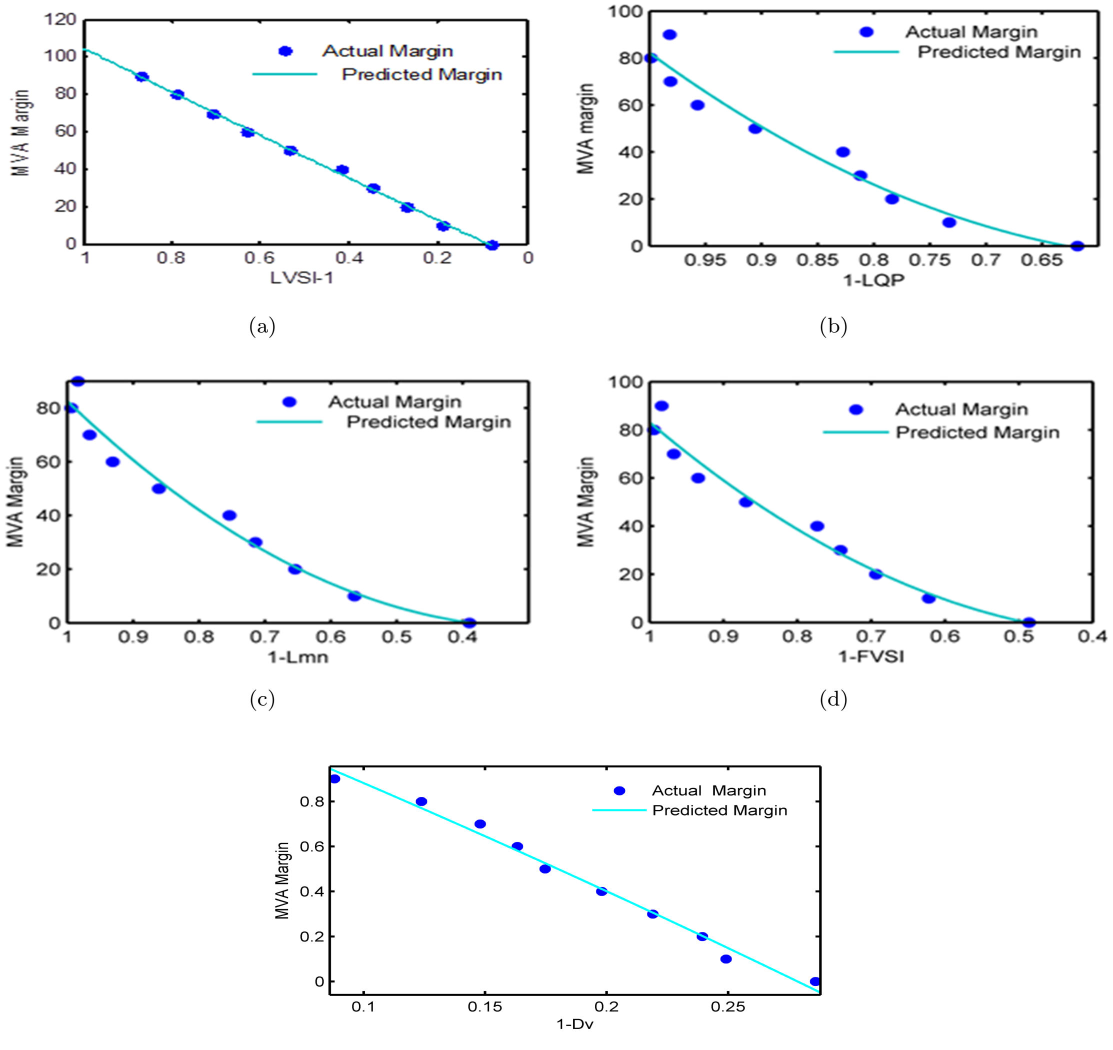
For the sake of comparison, the MVA margin of line (2-6) under different loading conditions is obtained using proposed method and other existing methods as shown in Table 3.16. From the Table, it is observed, that under all the loading conditions, the proposed index is giving nearly the same loading margin as the actual loading margin. However, the other methods are unable to accurately predict the loading margin. This shows the superiority of the proposed methods over other existing methods. In the voltage stability monitoring and control, the accurate prediction of MVA loading margin is highly desirable as any wrong prediction may lead to erroneous preventive control action.

TABLE 3.16: Prediction of MVA margin comparison for IEEE 30-bus system for line 2-6

Loading Factor	Actual MVA margin	MVA margin by Proposed Index	MVA margin by L_{mn} [65]	MVA margin by LQP [73]	MVA margin by $FVSI$ [72]	MVA margin by D_v [74]
1	173	173	174.75	172.95	174.73	173.05
1.1	163	162	109.47	163	104.24	161.88
1.2	153	153	126.64	149.41	127.26	152
1.3	143	143	126.9	143	126.21	143
1.4	133	131	133	135.8	134.73	130.81
1.5	123	120	117.9	122.86	116.97	121.90
1.6	113	114	133	120.75	135.81	112.76
1.7	103	103	129.62	109.75	131.5	102.59
1.8	93	93	120.05	99.81	120.01	91.78
1.9	83	83	108.78	88.35	108.08	81.95
2	73	73	96.1	76.45	94.05	72.54
2.1	63	63	81.18	64.19	78.58	62.87
2.2	53	53	64.79	53	62.93	51.41
2.3	43	43	47.87	39.01	45.91	40.23
2.4	33	33	29.25	26.99	29.59	32.81
2.5	23	23	12.37	15.92	14.8	22.96
2.6	13	13	0.122	7.76	3.98	12.79
2.7	3	3	1.09	5.69	3	2.98
2.73	0	0	9.14	6.12	6.62	0.15

B. Margin estimation of IEEE 118 bus system

The ability of proposed $LVSI$ in terms of MVA margin estimation is investigated on IEEE 118 bus system at a given operating point. $LVSI$ varies between 2 to 1 as loading increases from no load to MLP. Thus, $LVSI - 1$ is a source of estimation of MVA margin. The relationship is developed between MVA margin and $LVSI - 1$ as depicted in Fig. 3.6(a) for IEEE 118-bus test system respectively. It has also been compared with actual margin which is shown by dots points. As shown in Fig. 3.6(a), for loading factor $\lambda = 1.4$, the actual loading margin is 40 MVA. For this loading index $LVSI$ is 1.5336. From Fig. 3.6, the estimated MVA margin for this value of index is also 40 MVA, which indicates that MVA margin can be predicted to high degree of accuracy using proposed $LVSI$. For same loading, the MVA margin is also computed using indices LQP [73], L_{mn} [65] , $FVSI$ [72] and D_v [74] as shown in Figures 3.6(b)-3.6(e) and it is found to be 52.12 MVA, 53.17 MVA , 52.41 MVA and D_v margin 52.86 MVA respectively which are quite different from actual margin. It is to be noted down here that in L_{mn} [65], LQP [73], $FVSI$ [72] indices the margin is estimated by 1-Index, as their value varies from 0 to 1 from no load to MLP, whereas in D_v [74] index lies between 0.7-1.



(a) (b) (c) (d) (e)

FIGURE 3.6: MVA margin comparison for proposed index and other indices for IEEE 118-bus system

3.7 Summary

In this chapter a new voltage stability index, $LVSI$ has been developed and proposed for voltage stability assessment. The index is based on $ABCD$ parameters of transmission line. The value of index lies between 2 and 1. Value nearer to 2 is an indication of voltage stable state whereas value near to 1 indicates poor state of voltage stability. Critical states of lines can be monitored on the basis of proposed index and necessary preventive control action can be applied to avoid voltage instability. The index is also mapped to assess the voltage stability margin of the system. The salient features of the proposed method can be outlined as follows:

- Insensitive to nature of load.
- Simple index, only information of voltage phasors of different nodes required.
- Line resistance and line charging admittance accounted.
- Estimation of available loading margin.
- Assessment of maximum loadability of the system.
- Identification of weak lines, buses.
- Simultaneously monitoring of perilous condition of all the lines for voltage stability alertness.
- On line measurement of voltage stability.
- Assessment of viability of new lines from voltage stability point of view at the planning stage.
- Indication of local as well as global voltage stability.

The effectiveness of the proposed index has been thoroughly investigated and compared with other existing indices. The application results of the proposed index on standard IEEE bus systems under different operating conditions show that the proposed index can accurately predict voltage stability of power systems. The index can be used to carry out accurate contingency analysis and contingency ranking. The comprehensive application results show that the proposed voltage stability index may serve as a promising tool for voltage stability assessment under all operating conditions.

Chapter 4

Optimal coordination of OLTCs and SVCs for voltage stability improvement

In this chapter, role of on-load tap changing transformer on voltage stability has been investigated. It is observed from simulations that critical transformer loses its ability to raise the voltage after certain change in tap ratio. For identifying the critical transformer, an index is proposed. To cope up the problem of voltage instability owing to tap changing operation of OLTC, SVCs are installed. Taguchi method (TM) is employed to coordinate the tap changing operation of OLTC with SVC. A fuzzy based multi-objective optimization problem is formed which involves the determination of optimal tap settings of OLTCs, and sizing of SVCs so as to optimize the different parameters of power systems.

4.1 Introduction

It is important to note that the voltage stability of the system is sensitive to the tap changing operation of on-load tap changers (OLTC). With each tap change operation, the MW and MVAr loading on the EHV lines would increase, thereby increasing the reactive power loss and causing higher voltage drops. As a result, with each tap-changing operation, the reactive output of generators throughout the system would increase gradually and the generators may hit their reactive power capability limits, causing voltage instability problems.

Therefore, certain OLTCs show strange behavior. When their tapping is raised beyond a limit, secondary voltage is pulled down. Tap changing of these critical transformers must be blocked/ reversed thereafter to prevent voltage instability. There is a pressing need to study the behavior of OLTCs under different loading conditions. Very little work has been reported in the literature to find critical transformer and its possible range of tap settings to avoid voltage instability of the system. Considering the significance of critical transformer, an index is proposed in this chapter for identifying the critical transformer and its permissible range of tap setting.

Once the critical transformer is identified, voltage stability problem can be sorted out by providing reactive power support using shunt capacitors/flexible ac transmission system (FACTS) devices. Numerous studies have been carried out [95]-[96]. Many researchers have proposed different artificial intelligence (AI) techniques to coordinate OLTC operation with FACTS devices for voltage stability [98]-[108]. These AI techniques use more complicated search methods for optimization. These methods use iterative trial and error progress with large data sets which are comparatively time- consuming. Conversely, the Taguchi method (TM) is an effective tuning method which is well defined, systematic and simple in steps. Moreover, TM chooses a combination of factors (the factors which is to be altered) which are robust against the behavior of the system changes. The TM has an extra advantage of being cooperative to identify the sensitivity of each factor which is to be tuned for final objective function. Taguchi works on an orthogonal array (OA) and OA give all possible combinations, such that the best solution lies within the combinations. Taguchi method (TM) has been applied successfully to optimization problems in power systems [110]-[115]. Therefore, in this viewpoint TM is quite superior to AI methods. Tap positions of OLTC is discrete in nature. TM is better than other established AI techniques when variables are discrete in nature. TM has not been considered so far to find the optimal setting of OLTCs in the system so as to minimize active power loss and to improve voltage stability of the system. Considering the merits of Taguchi method, Taguchi based technique is employed to develop a proper strategy for optimal coordinated operation of

OLTCs with SVCs so as to improve the voltage profile and voltage stability margin, and to decrease real power loss of the system. SVCs are chosen for shunt compensation due to its simpler operation and lower cost in comparison to other FACTS devices.

The application of the proposed method has been investigated on IEEE 30-bus and IEEE 118 bus systems. Index for identification of critical transformer is derived in the following section:

4.2 Proposed Index for Identification of Critical Transformer

When system is voltage stable, change in voltage will be positive when tap ratio of OLTC is inreased. Negative change in voltage for positive change in tap ratio indicates critical condition of OLTC. Proposed index is based upon the sensitivity of voltage w.r.t. tappings. Negative sensitivity indicates critical transformer.

Fig. 4.1 desribes a two bus transmission network integrated with an OLTC. As per the Fig. 4.1, relation between sending end voltage V_S and receiving end voltage V_R are given by [109]

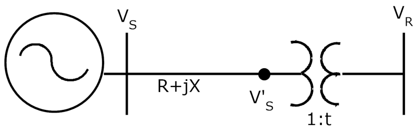


FIGURE 4.1: A radial line with tap changing transformer

$$V_S = V_S' + \frac{RP + XQ}{V_S'} \tag{4.1}$$

Where, P and Q are line flows, R and X are total resistance and reactance of line and transformer respectively. Eq. 4.1 can be rearranged as:

Sending and receiving ends voltages can be related by tap ratio t in the following way:

$$V_S' = \frac{V_R}{t} \tag{4.2}$$

Substituting Eq. 4.2 in Eq. 4.1, we have

$$V_S = \frac{V_R}{t} + \frac{(RP + XQ).t}{V_R} \tag{4.3}$$

Rearranging we have,

$$t.V_S V_R = V_R^2 + (RP + XQ).t^2 \tag{4.4}$$

Differentiating V_R with respect to tap ratio t, we get

$$t.V_S \frac{dV_R}{dt} + V_R.V_S = 2.V_R \frac{dV_R}{dt} + 2t.(RP + XQ) \tag{4.5}$$

$$\Rightarrow \frac{dV_R}{dt}[2V_R - V_S.t] = V_R V_S - 2.t(RP + XQ) \tag{4.6}$$

$$\Rightarrow \frac{dV_R}{dt} = \frac{V_R V_S - 2t(RP + XQ)}{2V_R - t.V_S} \tag{4.7}$$

OLTC can support the receiving end voltage with rise in tap ratio if sensitivity dV_R/dt must be positive.

$$\Rightarrow \frac{dV_R}{dt} > 0 \tag{4.8}$$

Proposed Tap Voltage Sensitivity Index *(TVSI)* can be defined on the basis of Eq. 4.8 as:

$$TVSI = \frac{V_R V_S - 2t(RP + XQ)}{2V_R - t.V_S} \tag{4.9}$$

Index *TVSI* of OLTCs must be positive to maintain voltage stability.

$$\Rightarrow TVSI > 0 \tag{4.10}$$

On the basis of index *TVSI*, operational tapping range of OLTCs can be determined. If proposed index of an OLTC shows negative value above a certain tap ratio (critical tap ratio), the OLTC is considered as critical and its tappings variations is restricted upto critical tap ratio.

After identification of critcal transformer and its critical range, the aim of research is to find optimal tap ratio of OLTCs and optimal sizing of SVCs so as to minimize the L-index and real power loss of the system. Optimal tap settings and size of SVC for getting lowest value of L-index and for getting minimum real power losses are different.Therefore, fuzzy logic method is applied to find the optimal solution. A brief description of L-index and Fuzzy set theory is presented in following sections:

4.3 L-index

Since SVCs are to be located at the buses, well established bus index, i.e. L-index [48] is chosen to check the impact of SVC on voltage stability. Voltage stability margin of the system can be expressed in terms of L-index. Its value ranges from zero (no load condition) to unity (voltage collapse). The load bus with the highest L- index value will be the most vulnerable bus in the system. The L-index can be expressed as:

$$L_j = 1 - |\sum_{i=1}^{g} F_{ji} * \frac{V_i}{V_j}| \tag{4.11}$$

Where, $j = g + 1, \ldots, n$; n represents the total number of buses, g denotes number of generator buses, and V_i and V_j are the complex values of bus voltages. The values of F_{ji} are obtained from the Y-bus matrix of the network.

The value of L_j for different load buses are calculated using Eq. 4.11 and the maximum value of L_j gives the proximity of the system to voltage collapse.

$$L = max(L_j) \tag{4.12}$$

An L-index value away from unity and close to zero indicates an improved voltage stability margin. Therefore, lower is the value of L-index; higher is the voltage stability margin.

4.4 Fuzzy Logic

Fuzzy set [142] proposed by Lotfi Zadeh in 1965. In fuzzy domain, each objective is linked with a membership function. These membership functions [143] indicate the degree of satisfaction of the objectives. Now a days, fuzzy logic method is used in diverse engineering applications. Many applications of fuzzy logic in power systems have been reported in [144].

Mathematically a fuzzy set F is defined as

$$F = \{(x, \mu_R(x))x\epsilon X\} \tag{4.13}$$

Where, X is a collection of objects denoted generically by x and $\mu_F(x)$ is called membership function for the fuzzy set F. The Membership Function (MF) allocates each element of X to a membership value in the interval [0, 1].

Fuzzy logic technique has been applied to transform the multi-objective optimization problem into a single objective optimization problem. In fuzzy domain, each objective is linked with a membership function. These membership functions indicate the degree of satisfaction of the objectives [143]. The multi-objective problem is formulated in fuzzy framework using a membership function. A trapezoidal membership function as shown in Fig 4.2 is used in this section to detect membership value of different objectives [143]. Maximum bound X_{max} and minimum bound X_{min} are different for different objectives.

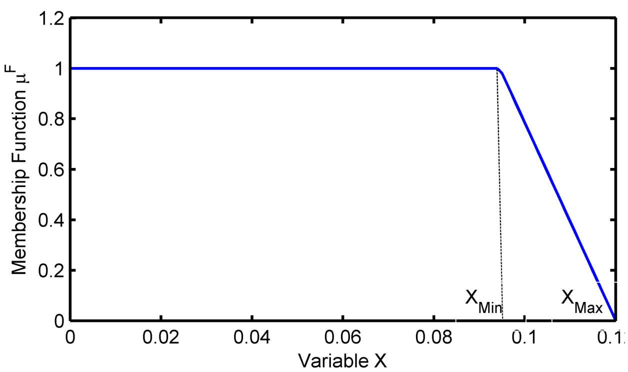


FIGURE 4.2: Trapezoidal fuzzy membership function

The proposed fuzzy function is defined as follows:

$$\mu^F(x) = \begin{cases} 0, & x > X_{max} \\ \frac{X_{max}-x}{X_{max}-X_{min}} & X_{min} \leq x \leq X_{max} \\ 1, & x < X_{min} \end{cases} \tag{4.14}$$

The degree of overall fuzzy satisfaction may be determined using composition operation. Max-geometric mean operator is used in the proposed work as it provides best compromising solution without the violation of any operating constraints [145]. The 'max-geometric mean' composition operation for the degree of overall fuzzy satisfaction can be defined as follow:

$$\mu^R = [\mu^1 * \mu^2 * ....\mu^n]^{1/2} \tag{4.15}$$

where μ^1, μ^2 ,..., μ^n are the fuzzy membership values of 'n' number of variables and μ^R is the degree of overall fuzzy satisfaction. In the thesis work, μ^L and μ^P denotes membership functions for L-index and real power loss respectively and degree of overall fuzzy satisfaction is defined as follows:

$$\mu^R = [\mu^P.\mu^L]^{1/2} \tag{4.16}$$

The fuzzified objective function is optimized using Taguchi Method in the proposed research work. A brief description of Taguchi Method is presented in the following section.

4.5 Taguchi Method

Taguchi Method (TM) is a process optimization method with minimum engineering resources. It is pioneered by Dr. Genichi Taguchi. TM is used in the proposed research to find optimal settings of tap positions of OLTCs to minimize the real power loss and L-index. TM offers a small set of combinations of tap settings for optimal solution. One of these combinations is optimal solution. The merit of TM over other AI technique is its higher probability of attaining optimal solution rather than the sub optimal solution and with less effort and time. TM is briefly discussed below to appreciate its application potential.

Consider an example where tap settings T_1, T_2, T_3 of three OLTCs is to be optimized for a given objective. It is assumed here that any of these OLTCs can have tap ratio either 0.9 or 0.95 (i.e. two levels; level 1and level 2). Where, level 1 indicates tap ratio 0.9 and level 2 indicates tap ratio 0.95. There will be eight possible combinations (i.e. design of experiments) of tap settings. One of these combinations will be optimum. TM optimally selects a subset of these possible solutions which can be tried and thus saves time and efforts. Optimally selected subset is referred as orthogonal array (OA). Table 4.1 shows an orthogonal array (OA) comprising of four best levels (L_4) of tap settings out of total 2^3 combinations.

TABLE 4.1: Orthogonal Array $L_4(2^3)$

Trial No.	Tap Levels			Fitness Value
	T_1	T_2	T_3	
1	1	1	1	$F_1^{'}$
2	1	2	2	$F_2^{'}$
3	2	1	2	$F_3^{'}$
4	2	2	1	$F_4^{'}$

Load flow is run with these four combinations of tap settings and fitness value of selected objectives is calculated for all these four cases. OLTC tap ratio is selected on the basis of trial which offers highest fitness value.

Suppose z and y represents total number of factors and levels in DOE, then the maximum possible number of design experiments

$$N = y^z \tag{4.17}$$

Degree of freedom (f) for a factor

$$f = y - 1 \tag{4.18}$$

Maximum number of Taguchi experiments

$$M = z * f + 1 \tag{4.19}$$

The representation of an OA is

$$L_M = y^z \tag{4.20}$$

The general steps engaged in TM are as follows:

1. Define the objective, or more specifically an optimal value to measure the performance of the process.
2. Identify the factors, which affect the operational process. The factors are variables, which affect the performance of output. The number of levels for factor variation must be specified.
3. Orthogonal Array (OA) for factorial design is created, which indicates the conditions of each experiment. The OA selection is based upon number of factors and the variation in levels.
4. Conduct the experimental trials for given OA to collect data for analyzing the effect of output value.
5. Complete the analysis to identify the optimal objective.

The flowchart of TM design of experiment is shown in Fig. 4.3

4.6 Problem Formulation

A new strategy is proposed in this section to solve multi-objective problem of minimizing the real power loss and L-index. Taguchi method has been applied to find optimal tap settings of OLTCs and sizing of SVCs so as to optimize the considered objectives

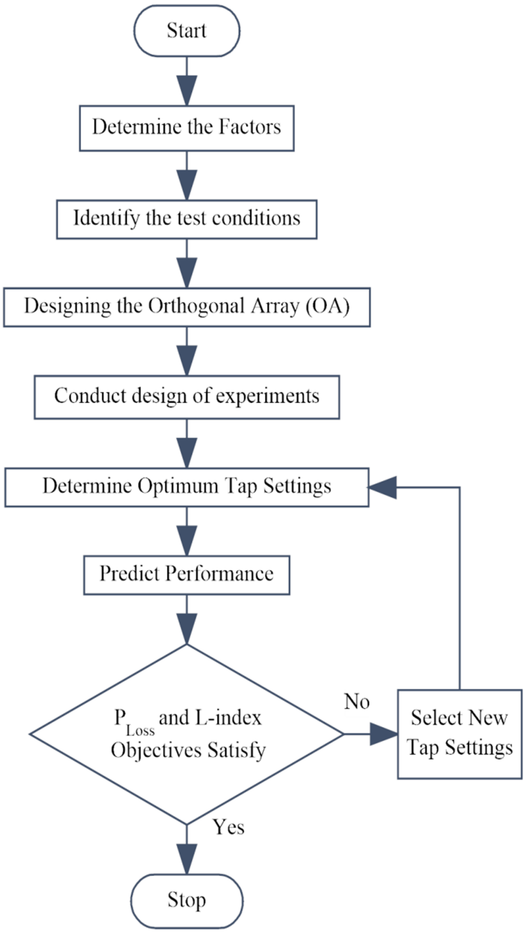


FIGURE 4.3: Flowchart representing Taguchi method

while considering different operating constraints [146]. The multi-objective problem is formulated in the following way:

The real power loss P_L of the system is the function of bus voltages, phase angles, and conductance of line which can be expressed as:

$$P_L = \sum_{x=1}^{n} G_{ij}(V_i^2 + V_j^2 - 2V_iV_jcos\theta_{ij}) \tag{4.21}$$

where i, j are end nodes of branch, G_{ij} is the branch conductance, V_i and V_j are voltage magnitudes at buses i and j respectively and θ_{ij} is the phase difference between sending end and receiving end voltages and n is the number of branches.

The membership functions for real power loss is μ^P .The purpose of this membership function is to find optimum OLTC tappings and sizing of SVCs so that real power loss of the system can be minimized. The membership function μ^P for the real power loss P_L is similar to the one shown in Fig. 4.2

From this figure; the membership function μ^P can be expressed

$$\mu^P = \begin{cases} 0, & P_L > P_L^{Max} \\ \frac{P_L^{Max} - P_L}{P_L^{Max} - P_L^{Min}} & P_L^{Min} \leq P_L \leq P_L^{Max} \\ 1, & P_L < P_L^{Min} \end{cases} \tag{4.22}$$

Higher value of μ^P indicates lower real power loss of the system.
The L –index of the system is given as:

$$L_j = 1 - |\sum_{i=1}^{g} F_{ji} * \frac{V_i}{V_j}| \tag{4.23}$$

$$L = max(L_j) \tag{4.24}$$

The rationale of membership function μ^L is to find optimal OLTC tappings and sizing of SVCs so that L-index of the system can be reduced. The membership function for the L-index (μ^L) is also similar to the one shown in Fig. 4.2. From this figure, the membership function (μ^L) is defined in the following way:

$$\mu^L = \begin{cases} 0, & L > L^{Max} \\ \frac{L^{Max} - L}{L^{Max} - L^{Min}} & L^{Min} \leq L \leq L^{Max} \\ 1, & L < L^{Min} \end{cases} \tag{4.25}$$

Higher value of μ^L indicates improved voltage stability margin of the system.
To obtain overall fuzzy satisfaction, 'max-geometric mean' as per equation (4.14) is used. Overall fuzzy function μ^R is defined as follows:

$$\mu^R = [\mu^P.\mu^L]^{1/2} \tag{4.26}$$

The optimization problem can be expressed as:

$$max(\mu^R) = max([\mu^P * \mu^L]^{1/2}) \tag{4.27}$$

The fitness function μ^R is maximized using Taguchi method subjected to the following constraints:

Equality Constraints:

Active power flow balance equation is given as:

$$P_{Gi} - P_{Di} = V_i \sum_{j=1}^{n} G_{ij} cos\theta_{ij} + B_{ij} sin\theta_{ij}) \tag{4.28}$$

Reactive power flow balance equation is given as:

$$Q_{Gi} - Q_{Di} = V_i \sum_{j=1}^{n} V_j (G_{ij} sin\theta_{ij} + B_{ij} cos\theta_{ij}) \tag{4.29}$$

where, P_{Gi} and P_{Di} are active power generated and active power demanded at node i, Q_{Gi} and Q_{Di} are reactive power generated and reactive power demanded at node i, G_{ij} and B_{ij} are branch conductance and branch susceptance respectively, and V_i & V_j are voltage magnitudes at buses i and j respectively.

Inequality Constraints:

- Limits of voltage magnitude

$$V_{Min} \leq V_i \leq V_{Max} \qquad \forall i = 1, 2, ...n \tag{4.30}$$

Where n is total no of buses in the system.

- Limits of tappings of OLTC

$$T_{Min} \leq T_i \leq T_{Max} \qquad \forall i = 1, 2, ...n \tag{4.31}$$

- Limits of active and reactive power

$$P_G^{Min} \leq P_G \leq P_G^{Max} \tag{4.32}$$

$$Q_G^{Min} \leq Q_G \leq Q_G^{Max} \tag{4.33}$$

Where V_{Min}, V_{Max}, T_{Min}, T_{Max}, are minimum and maximum values of voltages and OLTC tapings. P_G^{Min}, P_G^{Max}, Q_G^{Min}, Q_G^{Max}, are minimum and maximum value of generated active and reactive power.

The Taguchi method maximizes the overall fuzzy function μ^R expressed by Eq. 4.27. Higher value of μ^R denotes improved overall performance of the system in terms of L-index and real power loss. Simulation results for different cases are presented in following sections:

4.7 Simulation Results

In the present work, simulations are performed in MATLAB to investigate the behavior of OLTC and SVC to know their impact on voltage stability and line losses. Initially, the effect of tap changing operation of OLTC on performance of power systems is examined and critical transformer is identified using proposed index. Then, OLTC and SVC are considered independently for optimization of single objective to see the effectiveness of each device on voltage stability and line losses. For optimization proposed method is employed. Afterwards combined effect of OLTCs and SVCs is investigated using proposed formulation. OLTC reaches in the critical state for heavily loaded system, therefore the test results are performed for peak loading conditions on IEEE 30 and 118 bus systems. The following cases have been considered for the investigation:

Case- I: Investigation of role of OLTCs

Case- II: Investigation of role of SVCs

Case -III: Investigation of coordinated operation of OLTCs and SVCs

The application results of the studies provide the maximum possible improvement in each of the objective considered. The results of simulation studies are summarized below:

4.7.1 IEEE 30-Bus Test System

IEEE 30-bus test system contains four OLTCs ($T_1 - T_4$), connected in the lines 6-9, 6-10, 4-12, 27-28 respectively. The effect of tap changing operation of different OLTCs on parameters of power systems is investigated under different loading conditions. On the basis of the investigation, critical transformer is identified. Thereafter, TM is employed to find optimal tap-settings of OLTCs to minimize real power loss and L-index. Thereafter, effect of SVCs is investigated to find optimal sizing to minimize real power loss and L-index of the system. Subsequently both OLTCs and SVCs are investigated to minimize both real power loss and L-index of the system. The results of simulation are presented in the following sections:

- **Case I: Investigation of OLTCs operation**

OLTC operation under heavy loading may have detrimental effect on voltage stability and other parameters. Therefore in this section, the role of OLTC has been investigated to see its impact on different parameters of power systems under heavy loading. The results of studies are presented below:

a. Effect of tappings on different parameters of power systems

Variation of OLTC tapping's on nodal voltage is examined at peak load condition. Result is shown in Fig 4.4. The figure reveals that as tap ratio is increased from 0.9 – 1.100, the receiving end voltage of T_1-T_3 increases.But the case of T_4 is observed to be different. Secondary voltage of T_4 increases when tap ratio reaches 0.9625, thereafter voltage decreases and the pattern is continued as shown in Fig 4.4. The observation reveals that transformer T_4 loses its capability of maintining voltage profile and becomes critical transformer.

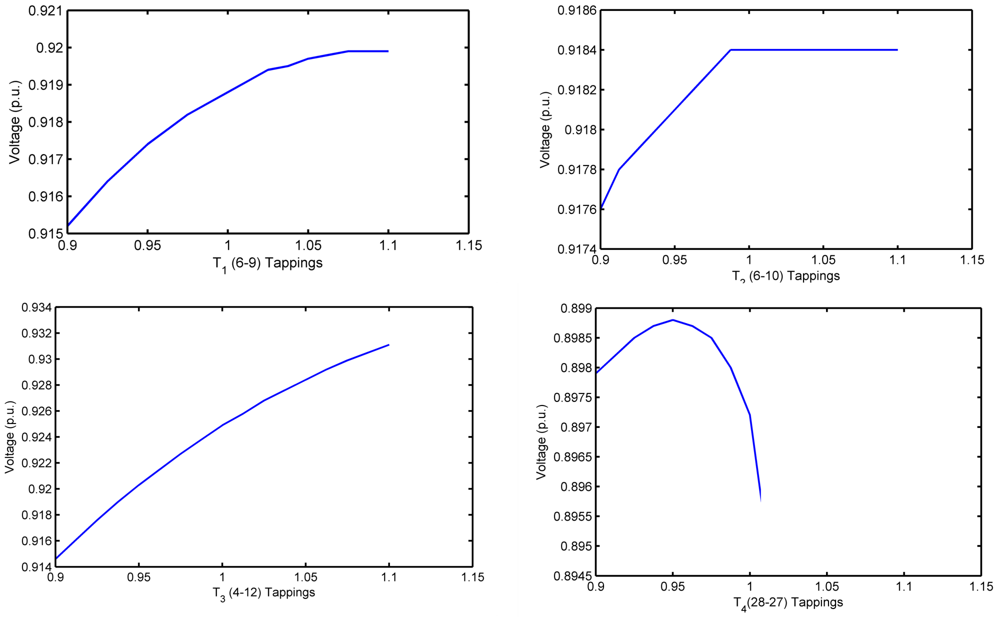


FIGURE 4.4: Tappings effect on voltages at peak loading for IEEE 30 bus

Effect of variation of tappings on line currents is also investigated. As shown in Fig 4.5, as tapping of T_1 is varied in the range of 0.900-1.100, the current in line 6-9 decreased from 0.4 p.u. to 0.1 p.u. The similar result is observed for transformer T_2. For transformer T_3, the current of line 4-12 decreased in the tap range of 0.9-0.9875, but above tap ratio 0.9875, current increases if tapping is raised. Similar pattern is observed for current in line 28-27 when tapping of transformer T_4 is varied.

Impact of variation of tappings of different OLTCs on active power loss of the system is also studied. Fig 4.6 shows the variation of tappings of T_1- T_4 on active power loss of the system. Power loss varied in the range 45.086 MW to 52.761 MW as tappings T_1- T_4 is varied from 0.900 to 1.100.

L-index varies in the range of 0 to 1 from no-load to full load condition. Higher values of L-index shows poor voltage stability margin. As shown in Fig 4.7 the L-index of the system is almost unaffected by variation in tappings of T_1, T_2, T_3. However, L-index is sharply increases as tap settings of transformer T_4 varies in between 0.9625 to 1.100.

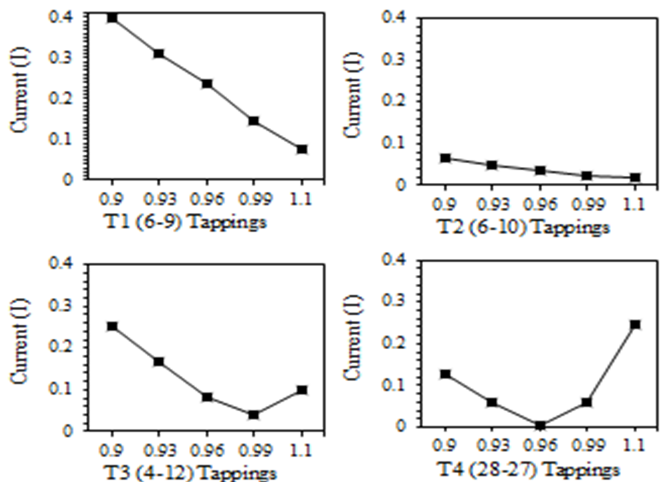


FIGURE 4.5: Effect of tappings on line currents at peak loading for IEEE 30 bus

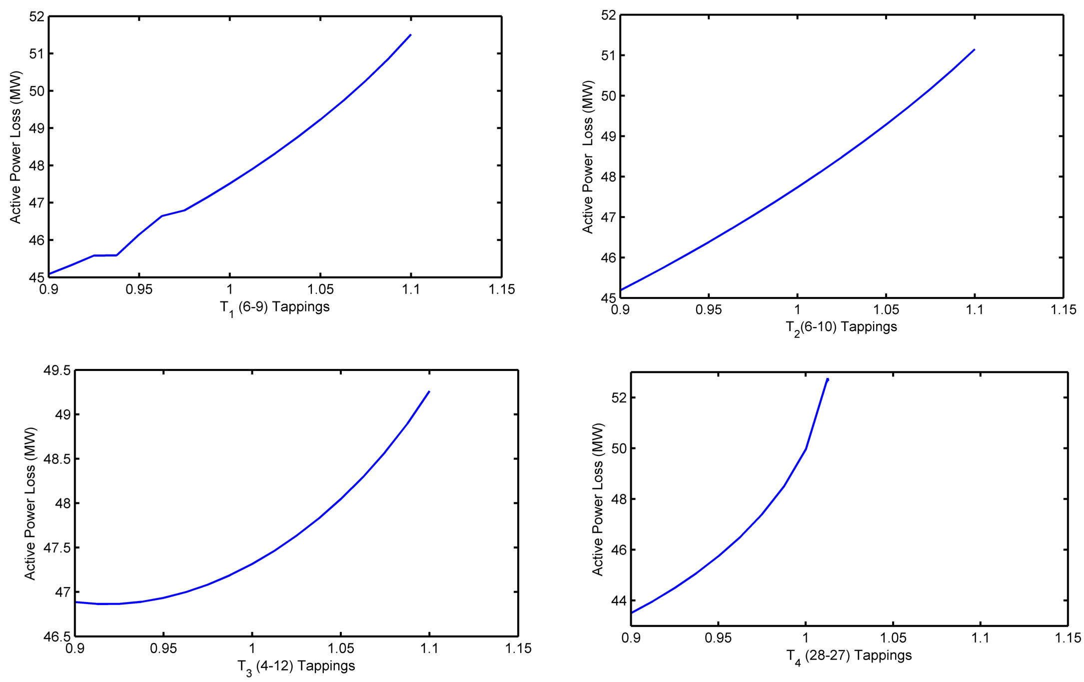


FIGURE 4.6: Active Power Loss for different tappings at peak loading for IEEE 30 bus

b. Identification of critical transformer using proposed index

Critical transformer is identified using proposed index. Index value of T_1-T_4 for different tap ratios is shown in Fig 4.8. It shows that index value is always positive for T_1, T_2, and T_3. Proposed index of T_4 is positive till tappings are raised to 0.9625. However,

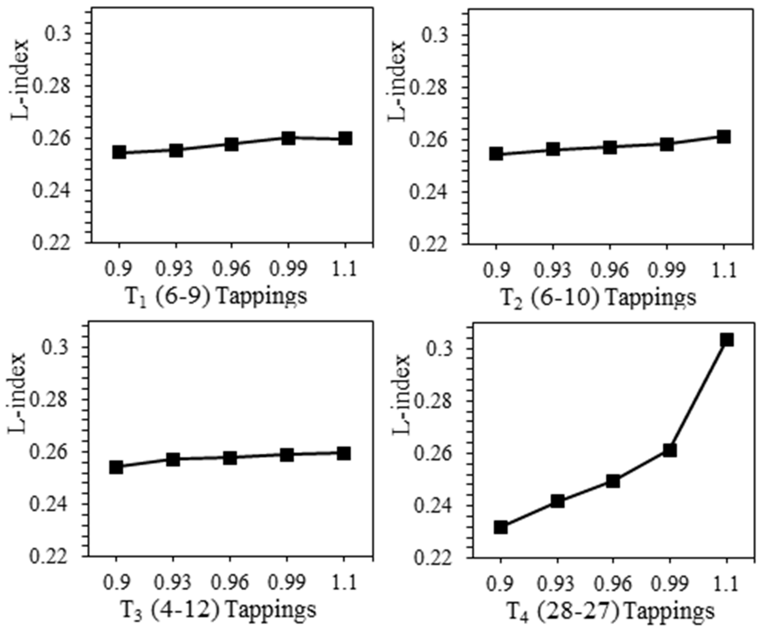


FIGURE 4.7: Effect of tappings on L-index at peak loading for IEEE 30 bus

beyond this tapping, index becomes negative. It shows that T_4 becomes critical when tap ratio is above 0.9625. Therefore, operational range of tappings of T_4 must be within 0.9-0.9625.

c. Optimal tap settings of OLTCs for minimization of real power loss

Once critical transformer is identified, its tap settings is varied in the range 0.9000 to 0.9625, since above 0.9625 tap ratio T_4 loses its effectiveness. Now objective is to find optimal tap settings of all OLTCs at heavy loading (149% of base load), so that real power loss can be minimized. For this purpose, Taguchi smaller the better method is employed. Tap settings of T_1 to T_3 is varied in the steps of 0.0125 in the range of 0.9-1.1, while for T_4, range 0.9 to 0.9625 is selected. Table 4.2 and Table 4.3 depicts possible tap settings and their levels. Level 1 of 1^{st} transformer shows a tap setting of 0.9, level 2 indicates tap settings of 0.9125 and so on. OLTCs T_1 to T_3 have 17 levels of tap settings while T_4 has only 6 levels. There will be 29,478 combinations of tappings of T_1, T_2, T_3, and T_4. TM optimally picks up only 102 combination to be tried for. It saves time and efforts significantly. The design of L_{102} OA is shown in Table 4.4. Out of these combinations, TM optimally selects best combination. Thus reducing the time and efforts significantly.

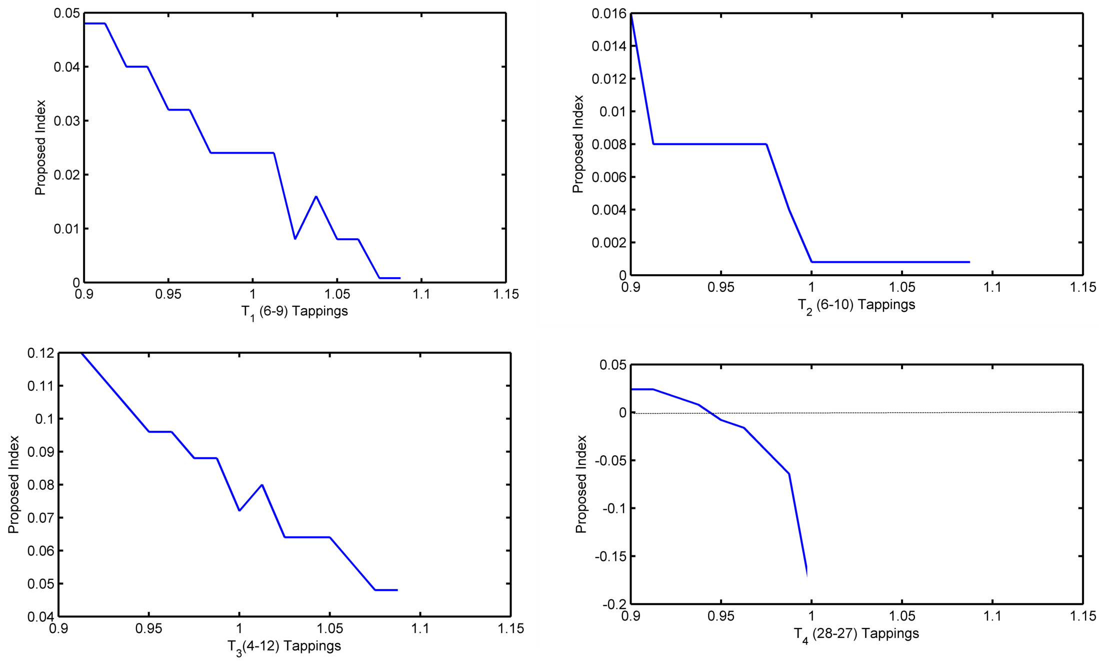


FIGURE 4.8: Change trends of proposed index for different OLTCs for IEEE 30 bus

The best combination of tap settings for 149% of base load is shown in Table 4.5. Optimal tap setting of T_1 to T_4 are found to be 1.100, 0.9875, 1.025, 0.9625 respectively.

TABLE 4.2: OLTCs with control factors and levels

Factors	Levels				
	L_1	L_2	L_3	–	L_{17}
OLTC T_1	0.9	0.9125	0.925	–	1.1
OLTC T_2	0.9	0.9125	0.925	–	1.1
OLTC T_3	0.9	0.9125	0.925	–	1.1

TABLE 4.3: Critical transformer with controlled levels

Factors	Levels of OLTC				
	L_1	L_2	L_3	–	L_6
OLTC T_4	0.9	0.9125	0.925	–	0.9625

Total active power loss of 43.052 MW is obtained, when tap settings is chosen according to the proposed method. Voltage and L-index of different buses are also compared and shown in Figures 4.9 and 4.10.

TABLE 4.4: L_{102} ($17^3 * 6^1$) orthogonal array factors and levels.

Trial No.	Levels of OLTC			
	T_1	T_2	T_3	T_4
1	1	1	1	6
2	1	4	10	4
-	-	-	-	-
-	-	-	-	-
100	17	6	7	4
101	17	8	11	2
102	17	9	13	1

TABLE 4.5: With and without optimal tap settings of OLTCs

Cases	T_1	T_2	T_3	T_4	Power Loss (MW)	L-index
Without Optimal Tappings	0.978	0.969	0.932	0.975	47.808	0.3014
With Optimal Tappings	1.100	0.9875	1.025	0.9625	43.052	0.2634

TABLE 4.6: Optimal tappings of OLTCs for minimum power loss at peak load of IEEE 30 bus system

Objective Function	Locations (from-to bus)	Optimal Tappings	Results Comparison		
			Particulars	Without Optimal Tappings	With Optimal Tappings
P_{Loss} *Minimization*	6-9 6-10	1.1 0.9875	P_{Loss}	47.808	43.052
	4-12 28-27	1.025 0.9625	L-index	0.3014	0.2634
L-index Minimization	6-9 6-10	1.05 0.9125	P_{Loss}	47.808	45.114
	4-12 28-27	0.9375 0.9625	L-index	0.3014	0.2514

d. Optimal tap settings for minimization of L-index

The OLTC tappings are also considered for enhancement of voltage stability margin which is determined using L-index. In this case, L-index is selected as objective function. OLTCs tappings are determined using proposed method. The results are shown in the Table 4.6. Optimally selected tappings decreases the L-index from 0.3014 to 0.2514 which

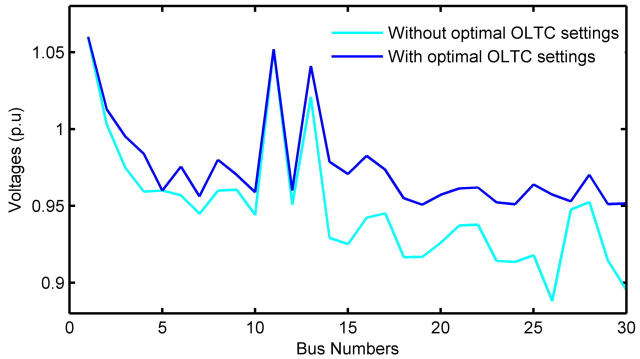


FIGURE 4.9: Voltage profile comparison with and without optimal OLTC tappings

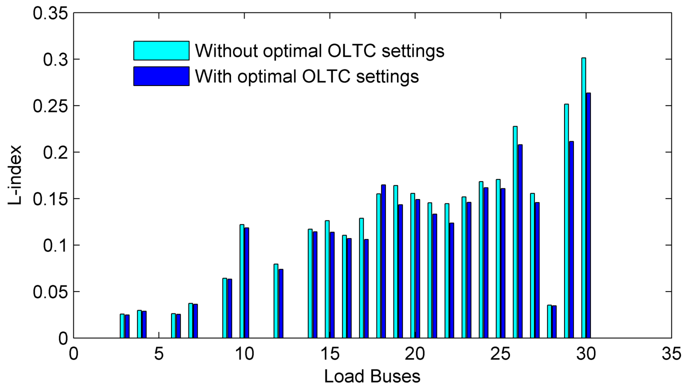


FIGURE 4.10: L-index comparison with and without optimal OLTC tappings

shows improved voltage stability margin. Line loss for this case are found to be 45.114 MW.

- **Case II: Investigation with SVCs operation**

Effectiveness of SVCs for enhancing voltage stability and reducing active power losses is also investigated to explore the potential of proposed method in order to find optimal size of SVCs. Optimal sizes of SVCs have been calculated using Taguchi's method(TM). First fuzzified objective function is formed to minimize the real power loss and L-index (i.e. to improve voltage stability margin). Then three locations are selected for placement of SVCs on the basis of [103]. After that objective function is minimized using TM. Taguchi's method offers a small set of combinations of optimal sizes of SVCs. One of these combinations that offer minimum value of objective function is selected as a solution. Sizes of SVCs for this combination are optimal sizes. The optimal number of SVCs to be placed has been chosen as three on the basis of [103].The optimal locations (bus no. 30, 29, and 26) for placements of SVCs are selected on the basis of L-index shown in Figure 4.11 Similar to the case of OLTC, in the beginning, each objective is considered independently for optimization. The results of simulation studies are presented in following sections:

a. *Optimal sizing of SVCs for minimization of real power loss*

The effect of SVC on active power loss of the system is investigated by selecting real power loss as objective function in Taguchi method. Table 4.7 shows that placing SVCs of optimum sizes 8.15, 3.1 and 10.14 MVAr at the optimal locations decreases real power loss from 47.808 MW to 44.512 MW. Therefore, SVC is less effective for the minimization of active power loss of the system. L-index for this case is also shown in the table.

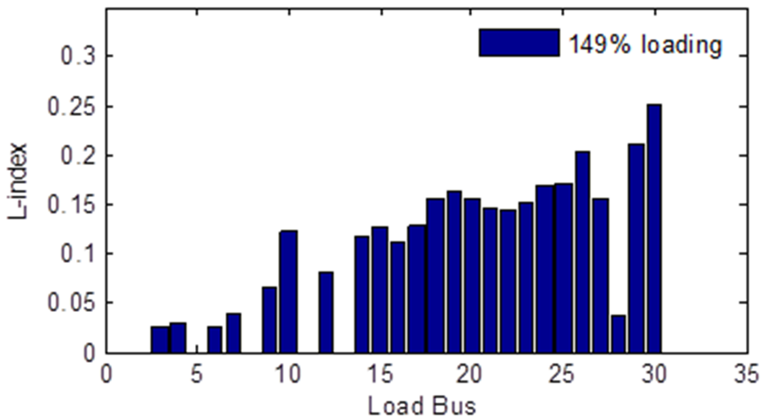


FIGURE 4.11: Variation of L-index at peak loading of IEEE-30 bus

TABLE 4.7: Optimal sizing of SVCs for minimum L-index at peak load of IEEE 30 bus system

Objective Function	Locations (Bus No.)	Optimal Sizing (MVAr)	Results Comparison		
			Particulars	Without Compensation	With Compensation
P_{Loss}*Minimization*	30 29 26	8.13 3.1 10.14	P_{Loss}	47.808	44.512
			L-index	0.3014	0.2382
L-index Minimization	30 29 26	8.5 3.8 11.04	P_{Loss}	47.808	45.114
			L-index	0.3014	0.2373

b. Optimal sizing of SVCs for minimization of L-index

The application of SVC is also investigated in the perspective of voltage stability. Table 4.7 clearly indicates that placing SVCs of optimum sizes on buses 30, 29, 26 reduce L-index from 0.3014 to 0.2373. The reduction in real power loss is less noticeable. Therefore, SVC is more effective for enhancing voltage stability of the system rather than minimizing active power loss of the system.

Figures 4.12 and 4.13 show the comparison of voltage profiles and L-index of uncompensated and compensated system respectively. It is observed that after optimal compensation, the voltage profile and voltage stability margin of the system is remarkably improved.

On the basis of cases I and II, it can be concluded that OLTC is more effective in decreasing line loss while SVC is better from the point of view of L-index minimization. Therefore, optimal coordination of OLTCs and SVCs are the most effective way of improving overall performance of the power systems.

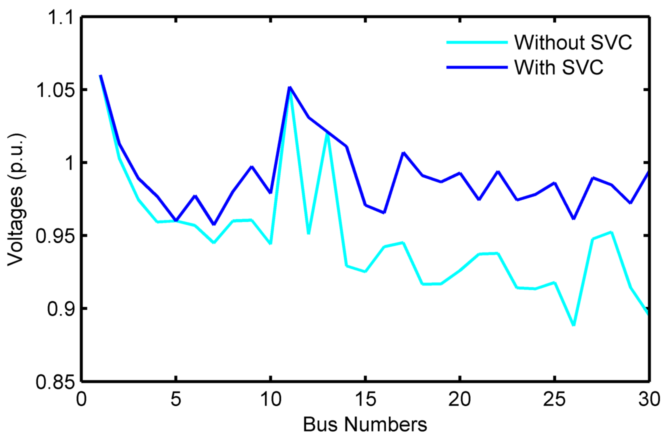


FIGURE 4.12: Voltage profile comparison with and without SVC placement

- **Case III: Optimal coordination of OLTCs and SVCs**

The effectiveness of OLTCs and SVCs for multi objective problem is examined by converting the multi-objective optimization problem into a single objective optimization problem through fuzzy approach. A trapezoidal membership function as shown in Fig. 4.2

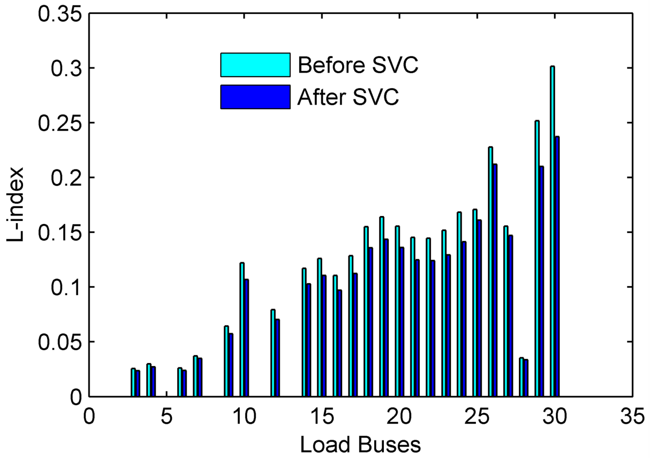


FIGURE 4.13: L-index comparison with and without SVC placement

has been chosen to determine membership values of variables. Lower and upper bounds of variables are chosen from Tables 4.6 and 4.7. The proposed optimization algorithm has been applied on the system using the limiting values shown in Table 4.8.

TABLE 4.8: Lower and upper bounds of variables at peak loading for IEEE 30 bus system

Objectives	Lower Bound	Upper Bound
P_{Loss}	43.052	47.808
L-index	0.2373	0.3014

Application results of optimal coordination of OLTCs and SVCs are shown in the Tables 4.9 and 4.10. SVCs are placed on the weak buses 30, 29 and 26 on the basis of L-index.

TABLE 4.9: Optimal OLTC tappings and optimal sizing of SVCs after coordination

Parameters	Optimal Results
$T_1(6-9)$	1.0875
$T_2(6-10)$	0.975
$T_3(4-12)$	1.0125
$T_4(28-27)$	0.9625
$SVC_{30}MVAr$	3
$SVC_{29}MVAr$	2.4
$SVC_{26}MVAr$	10.3

It is observed from Table 4.10 that performance of the system improved remarkably with coordination of OLTCs and SVCs. The active power loss decreased from 47.808 MW to 43.650 MW and voltage stability margin improved as L-index decreased from 0.3014 to 0.2491. The other parameters are also found to be satisfactory after the optimal coordination. For the sake of comparison overall degree of satisfaction μ_R is computed for all the cases and shown in Table 4.11.

Results of comparison show that overall degree of satisfaction μ_R is highest for the case –III. It shows that coordinated operation of OLTCs and SVCs is the best strategy for overall performance improvement of the system.

TABLE 4.10: Results for optimal coordination of OLTCs and SVCs for IEEE30-bus system

$P_{Loss}MW$	Without optimal OLTC settings and No SVC	47.808
	With optimal OLTC settings and SVC	43.650
L_{index}	Without optimal OLTC settings and No SVC	0.3014
	With optimal OLTC settings and SVC	0.2491
μ^L		0.8159
μ^P		0.8742
μ^R		0.8445

TABLE 4.11: Comparison of cases I to III for IEEE 30 bus system

Particulars	Only OLTCs (case-I)	Only SVCs(case-II)	Optimally coordinated OLTCs and SVCs (case-III)
Overall	0.7726	0.7525	0.8445

Voltage profile and L-index of an uncompensated and optimally coordinated system is shown in Figures 4.14 and 4.15 respectively which shows improved voltage profile and voltage stability margin.

The best, mean, and worst active power loss obtained using the SOA [147] , L-SaDE [147], PSO-cf [147], HDE [94] is compared with proposed method and summarized in Table 4.12. From the table, it is found that the proposed method provides better results as compared to other established methods.

Voltage profile and L-index of proposed method is also compared with [94] and shown in Figures 4.16 and 4.17 respectively. Voltage profile and voltage stability margin of the

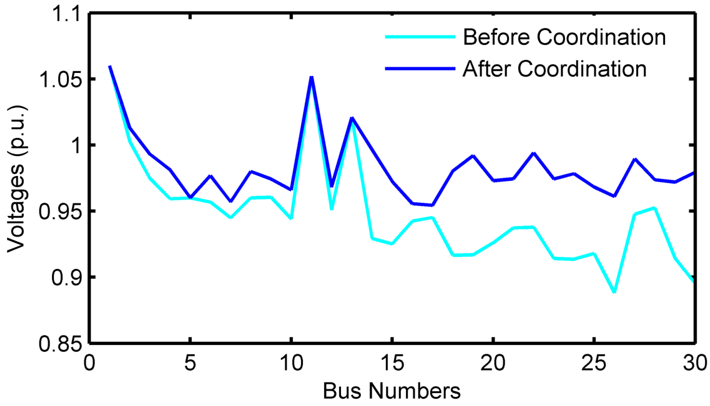


FIGURE 4.14: Voltage profile comparison before and after OLTC and SVC coordination

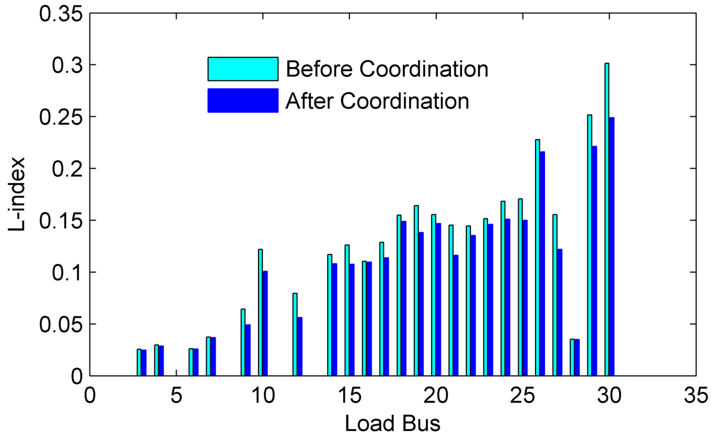


FIGURE 4.15: L-index comparison before and after OLTC and SVC coordination

TABLE 4.12: Simulation results for Active power loss obtained by different algorithms

	Active Power Loss (MW)					
	Without Coordination	SOA [147]	L-Sade [147]	PSO-cf [147]	HDE [94]	Proposed OLTCs and SVCs coordination
Best	47.808	44.02	45.7051	47.7444	46.121	43.65
Worst	47.808	54.565	48.9044	61.3191	-	49.094
Mean	47.808	49.292	47.3	54.53	NA	46.37

system are observed to be much better when OLTCs and SVCs are coordinated on the basis of proposed method as compared to HDE [94]. All of these results endorse the proposed methodology. Potential of proposed methodology is also investigated on a larger bus system. The results of investigation is presented in following section.

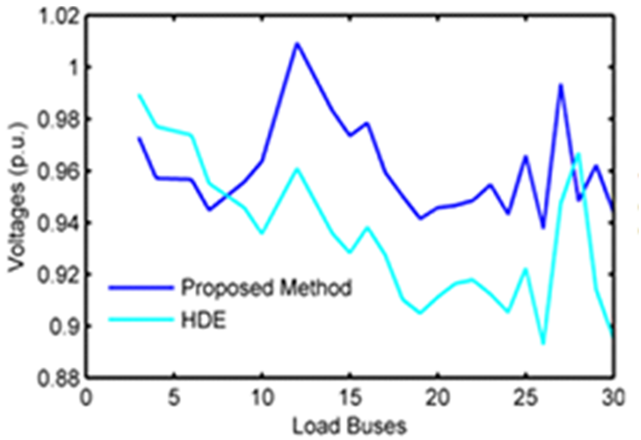


FIGURE 4.16: Voltage profile comparison between HDE and proposed method

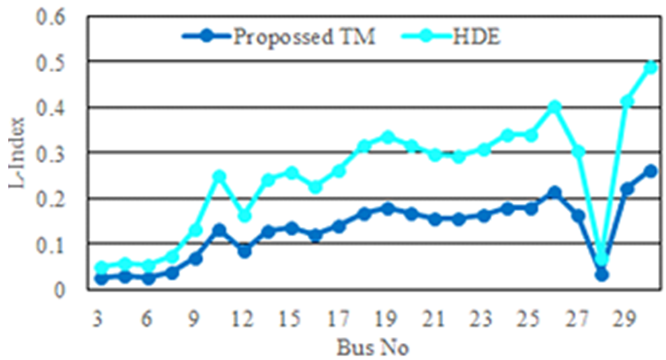


FIGURE 4.17: L-index comparison between HDE and proposed method

4.7.2 IEEE 118 Bus Test System

The performance of TM is further investigated on IEEE 118-bus test system [153]. Description of the system is depicted in Table 4.13. The system contains nine OLTC ($T_1 - T_9$) as shown in Table 4.8. The effect of tap changing operation of different OLTCs on parameters of power systems is investigated at peak loading condition. Then, critical transformer is identified on the basis of proposed index. TM is employed to find optimal tap-settings of OLTCs to minimize real power loss and L-index. Then, optimal sizing of SVCs is found on the basis of proposed method and its effect on voltage stability and real power loss is investigated. Subsequently role of OLTCs and SVCs are investigated to minimize real power loss and to improve voltage stability of the system through fuzzified taguchi approach. Results of simulation are presented in the following sections:

TABLE 4.13: Description for IEEE 118-bus test system

Description	IEEE 118-bus system
Buses	118
Generator, N_G	54
Transformers, T	9
Shunt Capacitors, SC	14
Branches	186
Equality Constraints	236
Inequality Constraints	572
Control Variables	77
Discrete Variables	21
Base Case P_{Loss} (MW)	132.45

TABLE 4.14: Location of OLTCs in IEEE 118-bus test system

OLTC	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9
Location	8-5	6-10	4-12	28-27	63-59	64-61	65-66	68-69	81-80

Case I: Investigation with OLTCs

OLTCs operation is also investigated on IEEE 118 bus system to see its impact on performnce of larger power system. Results of study is presented below.

a. Effect of tappings on different parameters of power systems

Variation of OLTC tapping's on nodal voltage is examined at peak load condition. Tap ratio is varied in the steps of 0.0125. Graphical variation of secondary voltage of $(T_1 - T_9)$ with tappings is shown in Fig. 4.18. It is obvious from this fig, that as tap ratio is varied from 0.9 – 1.100, the receiving end voltages of T_1, T_2, $T_4 - T_9$ increases. However, response of T_3 is different. Secondary voltage of T_3 increases in the tapping range of 0.9-0.955, thereafter voltage decreases continuously. This observation shows that transformer T_3 is a critical transformer and must be taken care of.

Effect of variation of tappings of $(T_1 - T_9)$ on line currents of corresponding transformers are also investigated. The graphical results are shown in Fig 4.19

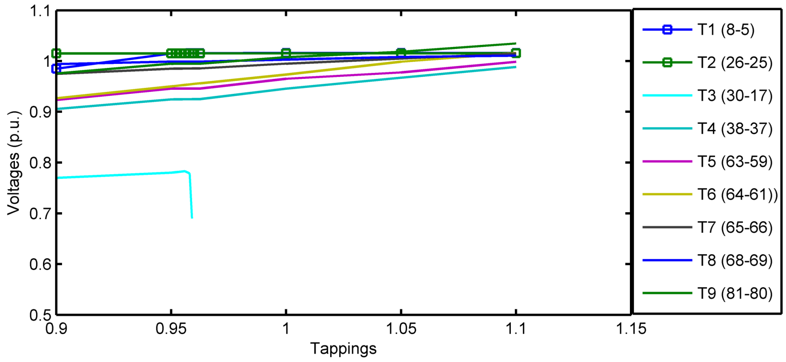


FIGURE 4.18: Effect of tappings on receiving end voltage for IEEE 118 bus

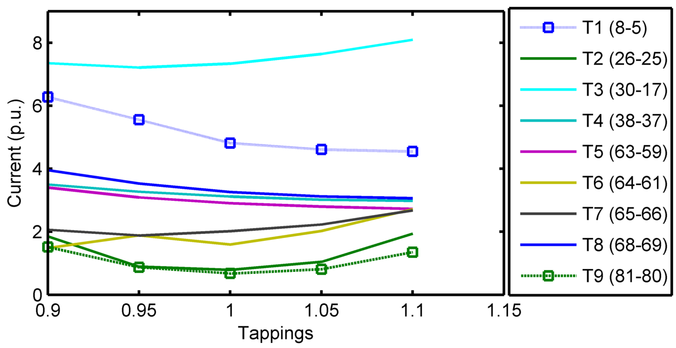


FIGURE 4.19: Effect of tappings on line currents for IEEE 118 bus

Active power loss of the system are also affected by tap changing operation of OLTC. Impact of variation of tappings of $(T_1 - T_9)$ on active power loss is shown in Fig. 4.20. Power loss varied in the range 382.058 MW to 389.7 MW as tappings of $(T_1 - T_9)$ is raised from 0.900 to 1.100. Variation of L-index with tappings of $(T_1 - T_9)$ is also investigated on larger bus system. The results are shown in Fig. 4.21.

b. Identification of critical transformmer using proposed index

Critical transformer for heaviliy loaded IEEE 118-bus system is identified using proposed index. Proposed index of $(T_1 - T_9)$ is noted down for different tap ratios and shown in Fig. 4.22. It is obvious from this graph that index value is always positive for T_1, T_2, $T_4 - T_9$. It shows that these transformers do not create voltage instability for their normal working range. Proposed index of T_3 is positive in the tapping range 0.9-

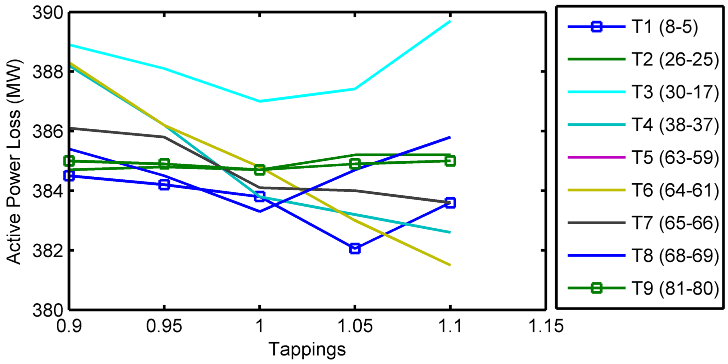


FIGURE 4.20: Effect of active power loss on receiving end voltage for IEEE 118 bus

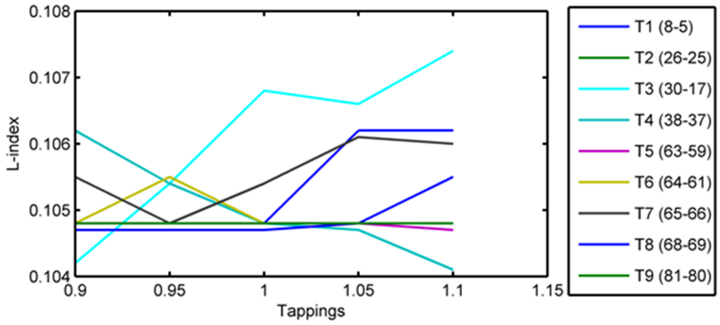


FIGURE 4.21: Effect of L-index on receiving end voltage for IEEE 118 bus

0.955. However, beyond this range, index is negative. It shows that T_3 acquire critical state when tap ratio is above 0.955. Therefore, operational tappings range of T_3 must be restricted within 0.9-0.955 to avoid voltage instability. Application results of IEEE 30 and 118 bus systems proves that proposed index is an useful index which can used to identify the criticality of transformer so as to maintain security and reliability of the system.

c. Optimal tap settings of OLTCs for minimization of real power loss

Reduction in the system active power loss is significant for economic reasons. OLTC operation can play a vital role in minimization of real power loss. To examine the role of OLTCs on larger bus system, real power loss is selected as objective function in the proposed formulation. The optimal tap settings of OLTCs are determined using Taguchi based proposed technique for minimum power loss. The simulation results are summarized

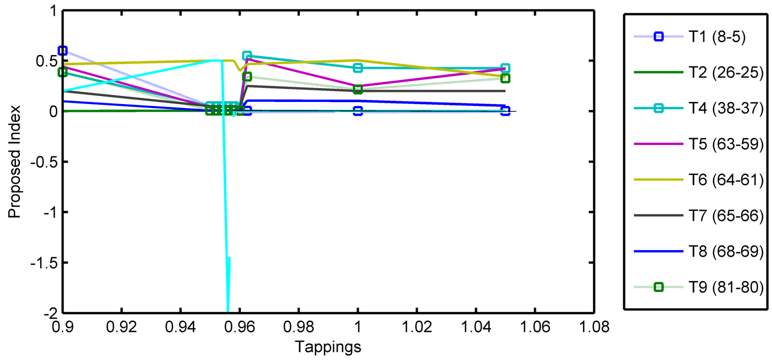


FIGURE 4.22: Change trends of proposed index on IEEE 118 bus

in Table 4.15. The optimal tap settings of OLTCs selected by TM are shown in the table. It is apparent from this table that properly selected tappings decreases active power loss from 394.229 MW to 367.123 MW. These results highlight the significance of OLTCs tappings for real power loss variations. L-index of the system for this case is also shown in the Table 4.15.

d. Optimal tap settings of OLTCs for minimization of L-index

The impact of OLTC tappings on voltage stability margin is also invesigated on larger bus system for the varification of results of IEEE 30-bus system. For this purpose, L-index is selected as objective function in the proposed Taguchi based optimization method. OLTCs tappings selected for T_1 to T_9 are shown in the Table 4.15. The L-index decreased from 0.1065 to 0.1049. Line loss for this case are found to be 391.84 MW which is higher when compared to the previous case.

Case II: Investigation with SVCs only

Proposed method is also investigated on IEEE 118- bus system to find optimal size of SVCs for minimization of L-index and real power loss of the system. Weak buses (bus no. 44, 45 and 95) are selected on the basis of L-index shown in Fig. 4.23 and three SVCs are placed on these buses [154]. Similar to the case of IEEE 30- bus system, initially, each objective is considered independently for optimization. Simulation results are presented in the following sections:

TABLE 4.15: Optimal tappings of OLTCs for different objectives at peak load for IEEE 118 bus system

Objective Function	Locations	Optimal tappings	Results Comparison		
			Particulars	Without Optimal Tappings	With Optimal Tappings
P_{Loss} Minimization	8-5	1.0875			
	26-25	0.9125			
	30-17	0.955	$P_{Loss}(MW)$	394.229	367.123
	38-37	0.9875			
	63-59	1.05			
	64-61	1.075			
	65-66	1.1	L-index	0.1065	0.1058
	68-69	0.925			
	81-80	0.9625			
L-index Minimization	8-5	1.05			
	26-25	1.0875			
	30-17	0.955	$P_{Loss}(MW)$	394.229	391.84
	38-37	0.9875			
	63-59	1.0125			
	64-61	0.9125			
	65-66	0.9			
	68-69	0.975			
	81-80	1.1	L-index	0.1065	0.1049

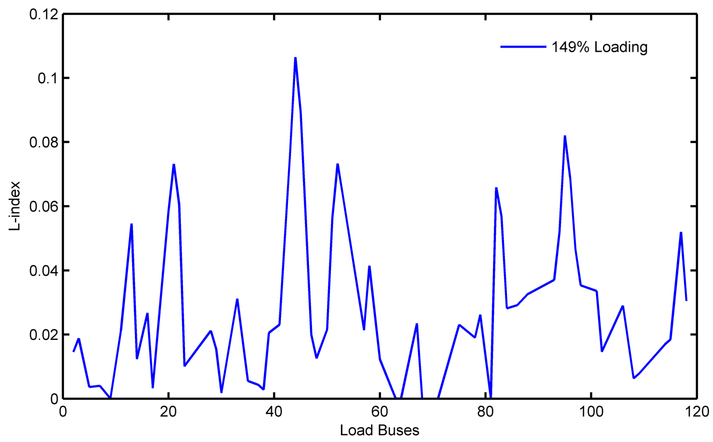


FIGURE 4.23: L-index of load buses at peak loading for IEEE 118 bus

a. *Optimal sizing of SVCs for minimization of real power loss*

For this case, real power loss is selected as a fitness function which is to be minimized using proposed method. Table 4.16 shows that SVCs of optimum sizes 1.1, 1.48, and 1.72 p.u. placed at the weak buses 44, 45 and 95 respectively decreases real power loss from 394.229 MW to 377.66 MW. L-index for this case is 0.1061.

Table 4.16: Optimal sizing of SVCs for different objectives at peak load for IEEE 118 bus system

Objective Function	Locations (Bus No.)	Optimal Sizing (p.u.)	Results Comparison		
			Particulars	Without Compensation	With Compensation
P_{Loss} Minimization	44	1.1	PLoss (MW)	394.229	377.66
	45	1.48			
	95	1.72	L-index	0.1065	0.1061
L-index Minimization	44	1.51	PLoss (MW)	394.229	375.66
	45	1.42			
	95	1.66	L-index	0.1065	0.095

b. Optimal sizing of SVCs for minimization of L-index

The role of SVC is also examined on IEEE 118- bus system for voltage stability improvement. L-index is selected as fitness function for the minimization. Table 4.16 clearly indicates that SVCs of optimum sizes 1.51, 1.42, and 1.66 p.u. placed on buses 44, 45 and 95 respectively reduces L-index from 0.1065 to 0.0950. Fall in L-index is more in this case. The reduction in real power loss is less noticeable as compared to previous case. Therefore, SVC is more effective for enhancing voltage stability rather than minimizing active power loss of the system.

The results of simulation on IEEE 118- bus system support the outcomes of IEEE 30-bus system that OLTC is more effective in decreasing real power loss while SVC is better from the point of view voltage stability improvement. It confirms the earlier findings, that overall performance of the power systems can be improved using optimal coordination of OLTCs and SVCs.

Case III: Optimal coordination of OLTCs and SVCs

In this case, real power loss and L-index are minimized using OLTCs and SVCs. The multi-objective optimization problem is converted into a single objective optimization problem using fuzzy approach. Membership values of variables are determined using trapezoidal membership function discussed earlier. Lower and upper bounds of variables selected from Tables 4.15 and 4.16 are shown in Table 4.17. The fuzzified objective function is minimized by the proposed method.

TABLE 4.17: Lower and upper bounds of variables at peak loading for IEEE 118 bus system

Objectives	Lower Bound	Upper Bound
P_{Loss}	367.12 MW	394.229 MW
L-index	0.095	0.1065

Optimal tap settings of $T_1 - T_9$ and optimum sizing of SVCs found using proposed method is shown in the Table 4.18 . SVCs are placed on the weak buses 30, 29 and 26 on the basis of L-index. Application results of optimization are shown in the Table 4.19 .

TABLE 4.18: Optimal OLTC tappings and optimal sizing of SVCs after coordination

Parameters	Optimal Results
T_1	1.0875
T_2	0.9625
T_3	1.05
T_4	0.975
T_5	0.9125
T_6	1.1
T_7	1.0125
T_8	0.9375
T_9	0.9875
SVC_{44} (p.u.)	1.83
SVC_{45} (p.u.)	1.65
SVC_{95} (p.u.)	1.73

It is observed from Table 4.19 that optimal coordination of OLTCs and SVCs improves voltage stability margin and decreases real power loss. The active power loss decreased from 394.229 MW to 367.565 MW and voltage stability margin improved as L-index decreased from 0.1065 to 0.0961. Overall performance of case-I to case-III is compared on the basis of μ^R as shown in Table 4.20.

Comparative results of these cases show that overall degree of satisfaction μ^R for case–III is 0.9426 which is the highest. It shows that for overall performance improvement of the system, OLTCs operation must be coordinated with SVCs using proposed optimization strategy.

TABLE 4.19: Optimal results for particular parameters at peak loading for IEEE 118 bus system

$P_{Loss}MW$	Without optimal OLTC settings and No SVC	394.229
	With optimal OLTC settings and SVC	367.565
L_{index}	Without optimal OLTC settings and No SVC	0.1065
	With optimal OLTC settings and SVC	0.0961
μ^L		0.9826
μ^P		0.9043
μ^R		0.9426

TABLE 4.20: Comparison of degree of satisfaction at peak loading for IEEE 118 bus system

Particulars	Only OLTCs	Only SVCs	Multi-objective OLTCs and SVCs coordination
Highest overall degree of satisfaction	0.7285	0.8275	0.9426

Voltage profile and L-index of uncompensated and optimally coordinated system is shown in Figures 4.24 and 4.25 respectively which shows improved voltage profile and voltage stability margin.

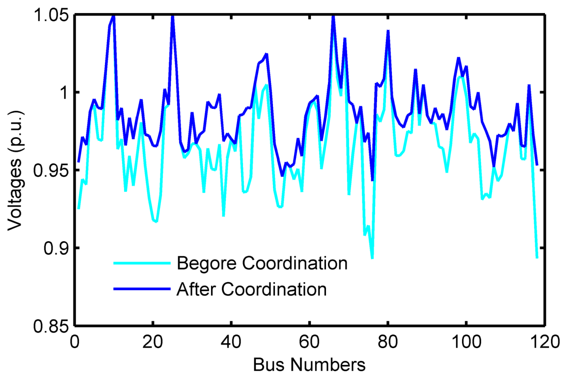


FIGURE 4.24: Voltage profile comparison before and after coordination under peak loading

The result is also compared with well-established techniques. The comparison of best, worst, and mean real power loss obtained using proposed and well-established methods (i.e. SOA [147] , L-SaDE [147] , PSO-cf [147], HDE [94]) is summarized in Table 4.21. It can be concluded on the basis of these results that the proposed method is better than other established methods.

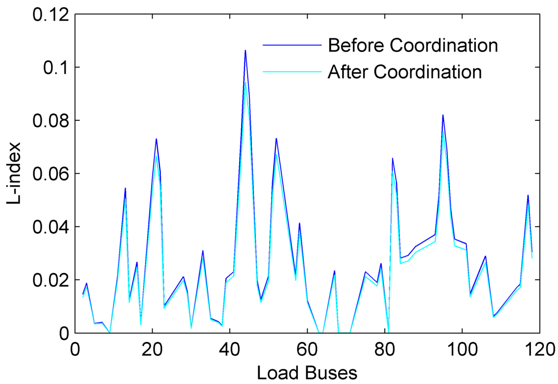


FIGURE 4.25: L-index comparison before and after coordination under peak loading

TABLE 4.21: Active power loss obtained by different algorithms for IEEE 118 bus system

	Active Power Loss (MW)					
	Without Coordination	SOA [147]	L-Sade [147]	PSO-cf [147]	HDE [94]	Proposed OLTCs and SVCs coordination
Best	394.229	378.06	392.28	396.81	380.35	367.565
Worst	394.229	409.71	421.29	554.46	-	407.997
Mean	394.229	393.88	406.78	475.63	-	387.781

4.8 Summary

The coordination of OLTCs tappings and SVCs is an important feature of power systems operation to extract maximum possible benefits in terms of power system performance improvement. In this chapter, a fuzzified TM based approach has been proposed for finding optimal tappings of OLTCs and optimal sizing of SVCs for enhancement in voltage stability margin and reduction in real power line loss of the power systems.

The multiple objectives of power systems have been transformed into a single objective function using fuzzy logic. In fuzzy domain, every objective is related with its membership function. The membership function indicates the degree of fuzzy satisfaction of the objective. In the proposed method trapezoidal fuzzy membership function is used to identify the membership values of each of objectives.

Initially effectiveness of OLTC tappings and SVCs for power system performance improvement has been investigated individually using TM on standard IEEE 30 bus and IEEE 118 bus systems and the application results are presented. These studies helped to identify the limiting values of different objectives which have been used to set the limits of the fuzzy membership function for multi-objective optimization problem. Then application of the proposed method has been investigated for multi-objective formulation on IEEE 30-bus and IEEE 118 bus systems. The following conclusions are drawn from this chapter:

1. The tapping variation of OLTC can be detrimental for voltage stability of the system under certain conditions.

2. Operational range of tappings of OLTCs must be known priorly for maintaining reliability and security of the system.

3. Critical transformer does not raise voltage above certain tap ratio. An index is proposed to identify the critical transformer.

4. SVC is more effective for minimization of L–index compared to minimization of real power loss of the system.

5. The coordination of OLTCs and SVCs is found to be the most effective strategy for minimization of L-index and active power loss of the system.

Chapter 5

Congestion Management using DGs and FACTS Controllers

Line congestion also leads to voltage instability [132]-[136]. Lines can be relieved from overloading conditions by placing Distributed Generator (DG) and FACTS devices of optimal size at appropriate locations. In this chapter, a new congestion margin index (CMI) is developed to measure the level of congestion in the transmission lines. To mitigate the problem of congestion and improving voltage stability, DGs and static synchronous compensators (STATCOM) are placed at suitable locations. A multi-objective fuzzified Taguchi method has been proposed in the chapter to determine the optimal sizing of DGs and STATCOMs for relieving line congestion and improving voltage stability. The proposed method is tested on standard IEEE 30 and 118 bus test systems.

5.1 Introduction

In a regulated power system network; generation, transmission and distribution are controlled by a vertically integrated utility, whereas in deregulated power system network, utilities like generation companies (GENCO), transmission companies (TRANSCO), distribution companies (DISCO), independent system operator (ISO), and retailer (RESCO) have a decisive role. The sole responsibility of ISO is to ensure proper security and reliability of power system. In the highly competitive environment, energy competitors try to maximise the use of available transmission resources to fulfill the desired energy transactions which leads to congestion in the existing transmission network.

Congestion management is one of the major challenges for reliable and secure operation of power system in a deregulated environment [137]-[139]. Very little work has been carried out in this area to measure level of congestion in the transmission networks. It motivated the author to develop a new congestion margin index (CMI) which can be used to identify the stressed lines and their critical ranking. The perilious condition of heavily loaded lines can be monitored on the basis of proposed index. To mitigate the problem of congestion, DGs can be placed at suitable locations. Various methods have been proposed by the [117] in the literature for placement of DGs for different applications. Though, use of DGs for the congestion management has not been given proper attention. Congestion of lines also leads to voltage instability which can be mitigated by placing STATCOMs of optimal sizing at voltage-weak buses. Many algorithms [126]-[129] has been suggested in the literature for optimal placement of STATCOM. However, the optimal coordination of DGs and STATCOMs is still a promising area of research. Considering the importance of coordination of DGs and STATCOMs for congestion management and voltage stability improvement, Taguchi based novel strategy has been proposed in this chapter.

5.2 Proposed Index

Every transmission line is designed to carry MVA load up to a certain limit. Gap between line limit and actual MVA flow is a measure of congestion margin of line. The proposed congestion margin index (CMI_j) of j^{th} line can be expressed as:

$$CMI_j = \frac{MVA^{Limit} - MVA^{Actual}}{MVA^{Limit}} \tag{5.1}$$

$$CMI = \sum_{j=1}^{L}(CMI_1, CMI_2, ..., CMI_L) \tag{5.2}$$

Where, L indicates total lines of the system. Negative value of (CMI_j) indicates that flow of j^{th} line is above prescribed limit. Lower positive value of CMI is an indication of lower MVA margin. A higher positive value of index is desirable to mitigate the problem of congestion.

5.3 Problem Formulation

Line congestion also leads to decrease in voltage stability margin. Voltage stability margin can be measured by L-index. Lower value of L-index shows higher margin. L-index can be decreased by placing STATCOM of optimal sizing at suitable locations. Placing DG at proper locations increases CMI and mitigates the problem of congestion. Therefore, a new strategy is required for maximizing the CMI and minimizing the L-index so that the problem of line congestion and voltage instability can be alleviated. These two objectives can be merged into single objective using proper fuzzy function. A new Taguchi based formulation is proposed in this section to solve multi-objective problem. The multi-objective problem is formulated in the following way. A trapezoidal membership function as shown in Fig 5.1 is used to find membership value μ^{CMI} of the index CMI in this section. The aim of this membership function is to maximize the MVA margin of the lines. Therefore, a higher value of μ^{CMI} is desirable. From this figure; the membership value μ^{CMI} can be expressed as:

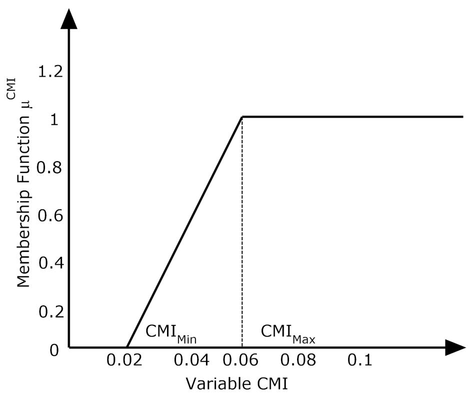


FIGURE 5.1: Trapezoidal fuzzy membership function for CMI index

$$\mu^{CMI} = \begin{cases} 0, & CMI < CMI^{Min} \\ \frac{CMI - CMI^{Min}}{CMI^{Max} - CMI^{Min}} & CMI^{Min} \leq CMI \leq CMI^{Max} \\ 1, & CMI > CMI^{Max} \end{cases} \tag{5.3}$$

Voltage stability margin is expressed by L-index. The L –index of the system is given as:

$$L_j = 1 - |\sum_{i=1}^{g} F_{ji} * \frac{V_i}{V_j}| \tag{5.4}$$

$$L = max(L_j) \tag{5.5}$$

All the variables used in L-index have the meaning similar to that used in *Chapter 4*. Lower value of L-index shows higher voltage stability margin. A trapezoidal membership function as shown in Fig 5.2 is used to find membership value μ_L of the L-index.

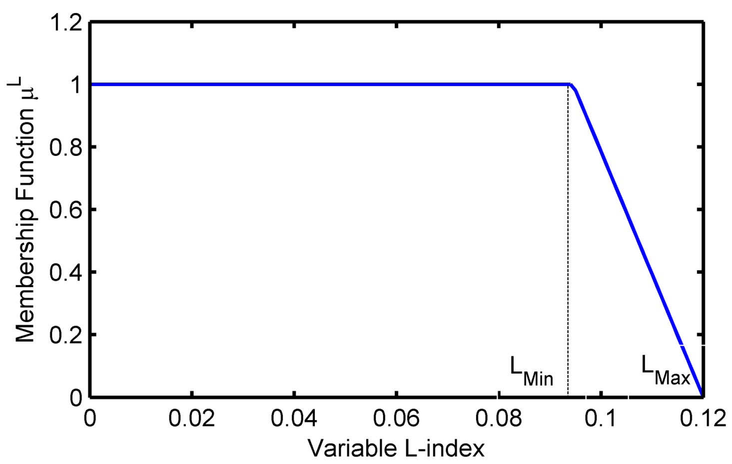


FIGURE 5.2: Trapezoidal fuzzy membership function for L-index

$$\mu^{L} = \begin{cases} 0, & L > L^{Max} \\ \frac{L^{Max} - L}{L^{Max} - L^{Min}} & L^{Min} \leq L \leq L^{Max} \\ 1, & L < L_{min} \end{cases} \tag{5.6}$$

The rationale of membership function (μ^L) is to minimize the L-index. Therefore, a higher value of (μ^L) is desirable.

For optimizing congestion margin and voltage stability margin, membership functions (μ^{CMI}) and (μ^L) can be merged into single objective using 'max-geometric mean'. Overall fuzzy function (μ^F) is now defined as:

$$\mu^F = [\mu^{CMI} * \mu^L]^{1/2} \tag{5.7}$$

The optimization problem can be expressed as:

$$max(\mu^F) = max([\mu^{CMI} * \mu^L]^{1/2}) \tag{5.8}$$

The Taguchi method is used to maximize the overall fuzzy function μ^F expressed by Eq. 5.8. Higher value of μ^F denotes improved overall performance of the system in terms of L-index and proposed congestion margin index. The proposed Taguchi based method has also been used for optimization of single objective in the research to see the effect of individual device on selected objective. Simulation results for different cases are presented in following sections:

5.4 Simulation Results and Discussion

The proposed congestion index has been investigated on standard IEEE 30-bus and IEEE 118-bus systems. The multiple objectives considered are; minimization of congestion in the lines and improvement in voltage stability of the system. Wind turbine based renewable DGs has been considered to be placed at appropriate locations to mitigate congestion in the transmission lines whereas STATCOM has been considered for enhancing voltage stability of the system. Different devices have different impacts on the performance of power systems. To explore the characteristics of individual device, initially, effectiveness of each device has been investigated for optimization of single objective. Thereafter, combined effect of these devices are examined. For this purpose, three cases has been considered :

- Case A: Investigation of DGs placement
- Case B: Investigation of placement of STATCOMs
- Case C: Investigation of coordinated placement of DGs and STATCOMs

The simulation results of the studies provide the maximum possible improvement in each of the objective considered. The results of simulation for IEEE 30 and 118 bus systems are presented in the following sections:

5.4.1 IEEE 30 Bus Test System

The proposed congestion margin index is tested on IEEE 30-bus test system. To reflect the congestion in lines, peak loading (149% of base case) is considered. On the basis of proposed index, critical lines which are violating their MVA limits are identified. The lines are ranked on the basis of proposed CMI index which is referred as CMI ranking. The study is carried for three cases; DGs placement, placement of STATCOMs , and combined placement of DGs and STATCOMs. Results of these studies are discussed in the following sections:

Case A: Investigation of DGs placement

The line flows, line limits, and proposed index for peak loading condition is shown in Table 5.1. CMI ranking of lines is shown in the Table 5.1. Lines with lower CMI values have high ranking. It is observed from this table that power flow in some lines (mark in bold letters) are flouting their MVA limits which is reflected by negative value of proposed CMI index of different lines. Power flow in many other lines are also near MVA limit. It shows insecure state of network. For maintaning security and reliability of network, and alleviating the overloading condition, DGs must be placed at the buses near the critical lines. These DGs deliver power directly to load, therefore lessening the power flows in the lines. Location of DGs is decided on the basis of CMI ranking of the lines.

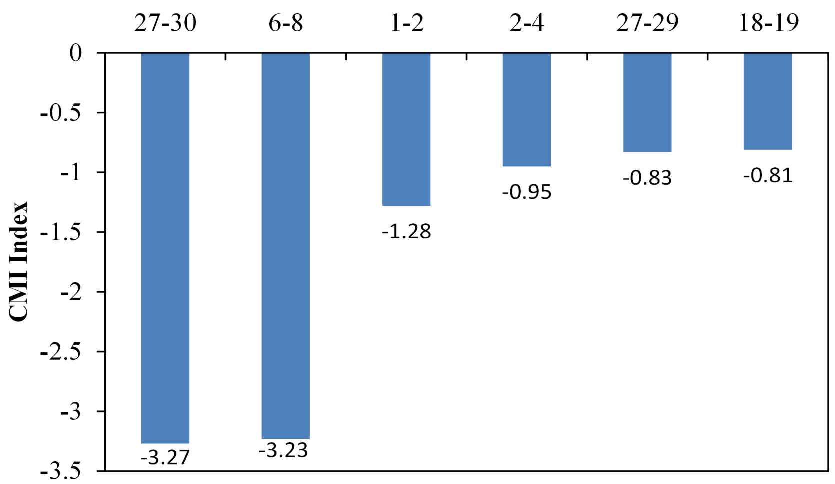


FIGURE 5.3: CMI index of overloaded lines of IEEE 30 bus system

The penetration level of DG in transmission system varies between 5%-25% as per reference [117]. However, in the simulations, 10% penetration of total load demand is considered. The numbers of DGs to be placed have been evaluated through proposed index. The comparative analysis for selection of optimal number of DGs through proposed CMI index is shown in Table 5.2. Form Table 5.2, it is observed that marginal change is observed in proposed index when no of DGs are increased from three to four. Therefore, three DGs are decided to be placed in the system. Maximum size of a DG is considered as 15 MW on the basis of penetration level. These DGs are placed at buses 30, 6 and 2 on the basis of CMI ranking. Impact of DGs for minimization of congestion in the lines is invetigated by proposed Taguchi based method. For this purpose, fuzzy membership functions(μ^{CMI}) is selected as a fitness function for maximization in the proposed method. The simulation results are summarized in Table 5.3.

The optimal sizing of DG obtained through proposed method is shown in Table 5.3. The line power flow after placing DGs of proper sizing at suitable locations is shown in Table 5.4. It shows that power flows in all the lines is within the limit which is reflected by the positive value of proposed index for different lines after DGs placement. It is observed from the Table 5.3 that placement of DG also increases CMI index of the system from 3.85 to 19.46 which indicate that DG is quite suitable for mitigating congestion problem in the lines. It signifies that proposed CMI index is a valuable index which can be used to identify the

Table 5.1: Apparent power flow of lines at peak loading of IEEE 30 bus

Branch (From-to)	MVA Limit	MVA power flow at peak loading	Proposed CMI Index	CMI Ranking
1-2	1.3	2.9722	-1.28631	3
1-3	1.3	1.3542	-0.04169	12
2-4	0.65	1.2704	-0.95446	4
3-4	1.3	1.2142	0.066	14
2-5	1.3	1.2704	0.022769	13
2-6	0.65	0.6839	-0.05215	11
4-6	0.9	1.2142	-0.34911	8
5-7	0.7	0.2934	0.580857	28
6-7	0.13	0.154	-0.18462	9
6-8	0.32	1.3542	-3.23188	2
6-9	0.65	0.4326	0.334462	18
6-10	0.32	0.3712	-0.16	10
9-11	0.65	0.3712	0.428923	23
9-10	0.65	0.475	0.269231	17
4-12	0.65	0.9355	-0.43923	6
12-13	0.65	0.2712	0.582769	29
12-14	0.32	0.1252	0.60875	31
12-15	0.32	0.2934	0.083125	15
12-16	0.32	0.1207	0.622813	32
14-15	0.16	0.0272	0.83	38
16-17	0.16	0.0597	0.626875	33
15-18	0.16	0.094	0.4125	21
18-19	0.16	0.2905	-0.81563	5
19-20	0.32	0.1078	0.663125	35
10-20	0.32	0.1465	0.542188	24
10-17	0.32	0.1028	0.67875	36
10-21	0.32	0.2858	0.106875	16
10-22	0.32	0.1369	0.572188	21
21-22	0.32	0.0296	0.9075	40
15-23	0.16	0.0921	0.424375	22
22-24	0.16	0.1044	0.3475	19
23-24	0.16	0.0379	0.763125	37
24-25	0.16	0.0269	0.831875	39
25-26	0.16	0.0644	0.5975	30
25-27	0.16	0.07	0.5625	26
28-27	0.65	0.2905	0.553077	25
27-29	0.16	0.0978	0.38875	20
27-30	0.16	0.6836	-3.2725	1
29-30	0.16	0.0565	0.646875	34
8-28	0.32	0.02	0.9375	41
6-28	0.32	0.4326	-0.35188	7

Table 5.2: Comparative analysis of CMI index for different number of DGs.

Parameter	Without DG	With single DG	With two DG	With three DG	With four DG
Proposed CMI Index	3.85	6.6	12.53	19.46	18.24

level of congestions in the system. The L-index also decreases marginally from 0.2516 to 0.2104.

Table 5.3: Optimal allocation of DGs for congestion index minimization

Objective Function	Locations (from-to bus)	Optimal Sizing (MW)	Results Comparison		
			Particulars	Without DG	With DG
$CMIMaximization$	30 6 2	14.94 14.65 14.05	CMI Index	3.85	19.46
			L-index	0.2516	0.2104

Effects of DGs placement on voltage profile and L-index is also observed. As shown in Fig. 5.4, there is a remarkable improvement in the voltage profile of the system. Voltage of all the buses are in the prescribed limit of 5% tolerance ($0.95 < V_j < 1.05$). L-index of the buses are also decreased which can be observed from Fig. 5.5.

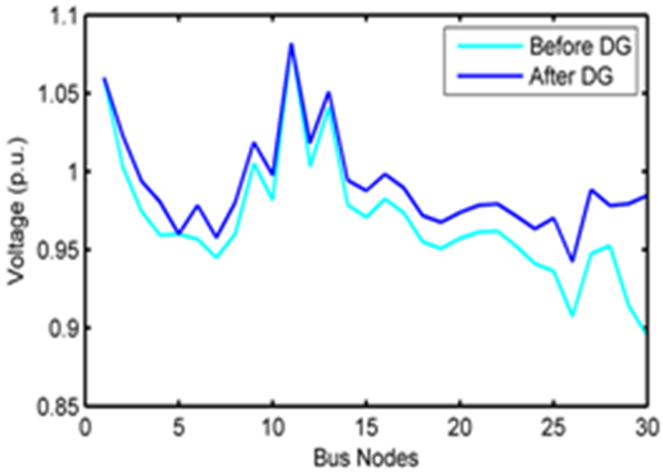


Figure 5.4: Voltage profile comparison before and after DG placement

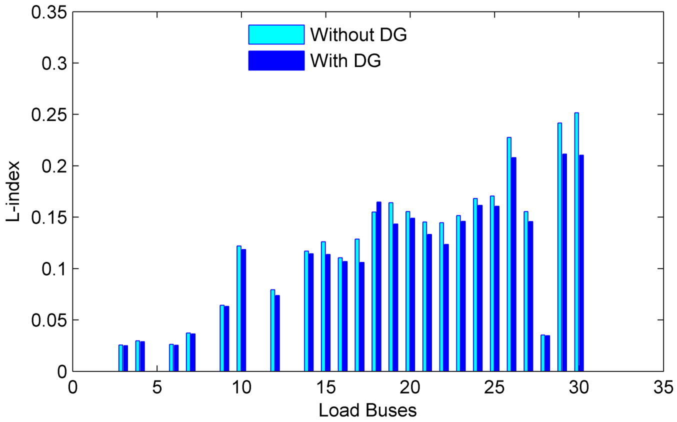


FIGURE 5.5: L-index comparison before and after DG placement

Case B: Investigation of placement of STATCOMs

The efficacy of STATCOM for enhancing voltage stability is investigated by incorporating STATCOMs at optimal locations. The suitable locations for placement of STATCOMs are selected on the basis of L-index of Fig. 4.11. Loading of the system is considered to be similar to case-A. The numbers of STATCOMs to be placed have also been decided using L- index. For this purpose fuzzy membership functions μ_L is selected as a fitness function for maximization in the proposed method. Maximization of μ_L implies minimization of L-index. In this case, proposed method is used for optimization of single objective. Initially, only one STATCOM is considered in the proposed method. The L-index decreased from 0.2516 to 0.1798. Then the procedure is repeated for two, three, and four number of STATCOMs. The effect of number of STATCOMs on L-index is shown in Table 5.5. From the Table 5.5, it is visible that there is a marginal decrease in L-index when number is changed from three to four. It shows that contribution of three STATCOMs for voltage stability improvement is almost same to that of four STATCOMs. Therefore, only three STATCOMs are placed from the economical point of view.

The location and sizing of STATCOMs selected for placement is shown in Table 5.6 It is observed from this table that L-index is reduced from 0.2516 to 0.1496 which shows noticeable improvement in voltage stability margin of the system. The effect of STATCOMs placement is also observed on line congestion. It is important to note from the Table 5.7 that even after optimal siting and sizing of STATCOM, congestion problem of

Table 5.4: Apparent power flow and congestion index of lines after optimal DG placement

Branch (From-to)	MVA Limit	MVA flow before DG	MVA flow after DG	Proposed CMI before DG	Proposed CMI after DG
1-2	1.3	2.9722	1.0861	-1.2863	0.1645
1-3	1.3	1.3542	1.0027	-0.0416	0.2286
2-4	0.65	1.2704	0.6504	-0.9544	0.0153
3-4	1.3	1.2142	0.9261	0.066	0.2876
2-5	1.3	1.2704	1.2029	0.0227	0.0746
2-6	0.65	0.6839	0.6399	-0.0521	0.0155
4-6	0.9	1.2142	0.8334	-0.3491	0.074
5-7	0.7	0.2934	0.2696	0.5808	0.6148
6-7	0.13	0.154	0.6251	-0.1846	0.1915
6-8	0.32	1.3542	0.3153	-3.2318	0.0146
6-9	0.65	0.4326	0.4104	0.3344	0.3686
6-10	0.32	0.3712	0.2291	-0.16	0.284
9-11	0.65	0.3712	0.1838	0.4289	0.7172
9-10	0.65	0.475	0.4071	0.2692	0.3736
4-12	0.65	0.9355	0.6316	-0.4392	0.0283
12-13	0.65	0.2712	0.1778	0.5827	0.7264
12-14	0.32	0.1252	0.1147	0.6087	0.6415
12-15	0.32	0.2934	0.2538	0.0831	0.2068
12-16	0.32	0.1207	0.0977	0.6228	0.6946
14-15	0.16	0.0272	0.0173	0.83	0.8918
16-17	0.16	0.0597	0.0397	0.6268	0.7518
15-18	0.16	0.094	0.0856	0.4125	0.465
18-19	0.16	0.2905	0.0357	-0.8156	0.7768
19-20	0.32	0.1078	0.117	0.6631	0.6343
10-20	0.32	0.1465	0.1558	0.5421	0.5131
10-17	0.32	0.1028	0.1277	0.6787	0.6009
10-21	0.32	0.2858	0.2121	0.1068	0.3371
10-22	0.32	0.1369	0.0985	0.5721	0.6921
21-22	0.32	0.0296	0.0965	0.9075	0.6984
15-23	0.16	0.0921	0.0561	0.4243	0.6493
22-24	0.16	0.1044	0.1097	0.3475	0.3143
23-24	0.16	0.0379	0.0132	0.7631	0.9175
24-25	0.16	0.0269	0.1057	0.8318	0.3393
25-26	0.16	0.0644	0.0641	0.5975	0.5993
25-27	0.16	0.07	0.1472	0.5625	0.08
28-27	0.65	0.2905	0.1305	0.553	0.7992
27-29	0.16	0.0978	0.0218	0.38875	0.8637
27-30	0.16	0.6836	0.0334	-3.2725	0.7912
29-30	0.16	0.0565	0.0358	0.6468	0.7762
8-28	0.32	0.02	0.0436	0.9375	0.8637
6-28	0.32	0.4326	0.1957	-0.3518	0.3884
			$\sum$	3.85	19.46

Table 5.5: Comparative study for effect of STATCOMs for IEEE 30 bus system

Parameter	Without STATCOM	With single STATCOM	With two STATCOMs	With three STATCOMs	With four STATCOMs
L-index	0.2516	0.1798	0.1704	0.1496	0.14574

the lines is not fully alleviated. Few lines are still carrying load above permissible limit. The overall CMI index is increased from 3.85 to 8.70. Therefore, optimal placement of STATCOM is not enough to relieve congestion problem, however voltage stability of the system is significantly improved.

TABLE 5.6: Optimal allocation of STATCOMs for L-index minimization

Objective Function	Locations (from-to bus)	Optimal Sizing (MVAr)	Results Comparison		
			Particulars	Without Compensation	With Compensation
$L-indexMinimization$	30 29 26	35.20 10.44 17.26	CMI Index	3.85	8.7085
			L-index	0.2516	0.1496

Fig. 5.6 depicts the bus voltage profiles before and after STATCOM placement for all the buses of the system. It is observed that after optimal STATCOM placement, the voltage profile is improved and lies in 5% tolerance range ($0.95 \leq Vj \leq 1.05$). Moreover, as shown in Fig. 5.7, there is a considerable improvement in voltage stability margin of the buses as L-index of all the load buses after compensation, is found to be lower than without compensation.

On the basis of cases A and B, it can be concluded that DG is more effective for mitigating line congestion while STATCOM is better from the point of view of L-index minimization. Since line congestion and voltage instability are correlated, optimal coordination of DGs and STATCOMs is the most effective strategy to deal with the problem of line congestion and voltage instability of the power systems. Results based upon the coordination are presented in next section:

- ***Case C: Investigation of coordinated placement of DGs and STATCOMs***

Line congestion mitigation and voltage stability improvement using optimal placement of DGs and STATCOMs is a multi objective problem which can be transformed into a single objective optimization problem using fuzzy logic technique. Trapezoidal fuzzy functions as shown in Figures 5.1 and 5.2 have been used to find membership values of μ^{CMI} and μ^{L} respectively. Upper bound of CMI index and lower bound of L-index is chosen corresponding to base case value. The lower bound of CMI index and upper bound

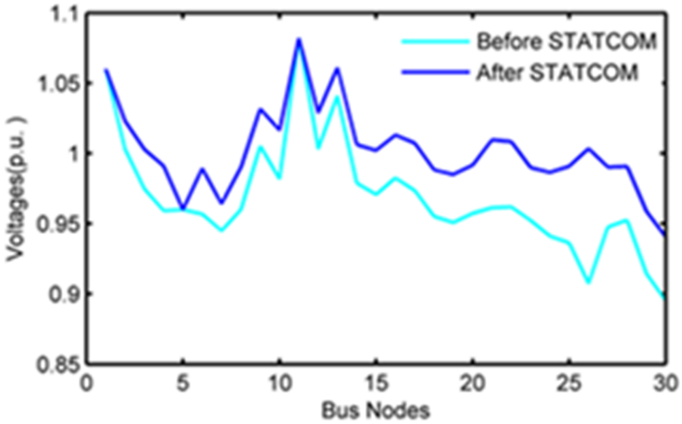


FIGURE 5.6: Voltage profile comparison before and after STATCOM placement

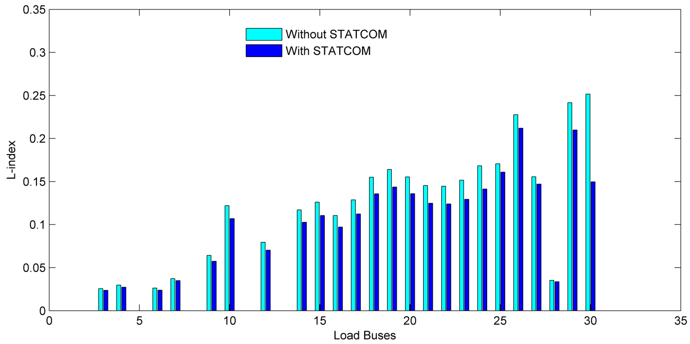


FIGURE 5.7: L-index comparison before and after STATCOM placement

of L-index is chosen from Table 5.3 . The upper and lower limits of variables of different objectives are shown in Tables 5.8 and 5.9. The results of cases A to C are also compared on the basis of their overall fuzzy function.

The proposed method is then used for maximizing overall fuzzy function μ^F expressed by Eq. 5.8 to investigate the coordinated combination of DGs and STATCOMs for line congestion mitigation and voltage stability improvement. The results of optimization are shown in Tables 5.10 and 5.11.

Results comparison of Table 5.11 with Table 5.3 and Table 5.6 suggests that optimal coordination of DGs and STATCOMs yields best solution among different objectives under peak loading condition. It is also perceived from Table 5.11 that performance of the system

TABLE 5.7: Apparent power flow and congestion index of lines after optimal STATCOM placement

Branch (From-to)	MVA Limit	MVA flow before STATCOM	MVA flow after STATCOM	Proposed CMI before STATCOM	Proposed CMI after STATCOM
1-2	1.3	2.9722	2.9505	-1.2863	-1.26962
1-3	1.3	1.3542	1.3467	-0.0416	-0.03592
2-4	0.65	1.2704	0.6861	-0.9544	-0.0555
3-4	1.3	1.2142	1.2318	0.066	0.05246
2-5	1.3	1.2704	1.2522	0.0227	0.03676
2-6	0.65	0.6839	0.9495	-0.0521	-0.4607
4-6	0.9	1.2142	1.1606	-0.3491	-0.2895
5-7	0.7	0.2934	0.2357	0.5808	0.6632
6-7	0.13	0.154	0.5898	-0.1846	-3.5369
6-8	0.32	1.3542	0.4843	-3.2318	-0.5134
6-9	0.65	0.4326	0.4353	0.3344	0.3303
6-10	0.32	0.3712	0.2366	-0.16	0.2606
9-11	0.65	0.3712	0.2066	0.4289	0.6821
9-10	0.65	0.475	0.4152	0.2692	0.3612
4-12	0.65	0.9355	0.6572	-0.4392	-0.0110
12-13	0.65	0.2712	0.2056	0.5827	0.68369
12-14	0.32	0.1252	0.1165	0.6087	0.6359
12-15	0.32	0.2934	0.2683	0.0831	0.1615
12-16	0.32	0.1207	0.1071	0.6228	0.6653
14-15	0.16	0.0272	0.0203	0.83	0.8731
16-17	0.16	0.0597	0.0528	0.6268	0.67
15-18	0.16	0.094	0.0889	0.4125	0.4443
18-19	0.16	0.2905	0.039	-0.8156	0.7562
19-20	0.32	0.1078	0.1143	0.6631	0.6428
10-20	0.32	0.1465	0.153	0.5421	0.5218
10-17	0.32	0.1028	0.1273	0.6787	0.6021
10-21	0.32	0.2858	0.2337	0.1068	0.2696
10-22	0.32	0.1369	0.1108	0.5721	0.6537
21-22	0.32	0.0296	0.0332	0.9075	0.8962
15-23	0.16	0.0921	0.0703	0.4243	0.5606
22-24	0.16	0.1044	0.0791	0.3475	0.5056
23-24	0.16	0.0379	0.0428	0.7631	0.7325
24-25	0.16	0.0269	0.1007	0.8318	0.3706
25-26	0.16	0.0644	0.2188	0.5975	-0.3675
25-27	0.16	0.07	0.1458	0.5625	0.0887
28-27	0.65	0.2905	0.2978	0.553	0.5418
27-29	0.16	0.0978	0.0968	0.38875	0.395
27-30	0.16	0.6836	0.1101	-3.2725	0.3118
29-30	0.16	0.0565	0.0563	0.6468	0.6481
8-28	0.32	0.02	0.077	0.9375	0.7593
6-28	0.32	0.4326	0.4893	-0.3518	-0.5290
			$\sum$	3.85	8.7085

TABLE 5.8: Lower and upper bounds for CMI at peak loading

Objectives	Upper Bound	Lower Bound
CMI	21.293	3.85

noticeably improved with coordination of DGs and STATCOMs. The congestion index increases from 3.85 to 20.3384 and voltage stability margin also enhanced as L-index reduces from 0.2516 to 0.1527. For the sake of comparison, results of cases A to C of IEEE

TABLE 5.9: Lower and upper bounds for L-index at peak loading

Objectives	Lower Bound	Upper Bound
$L - index$	0.1366	0.2516

TABLE 5.10: Optimum location and sizing of DG and STATCOM after coordination

Parameters	Optimal Results
$DG_{30}(MW)$	14.81
$DG_6(MW)$	14.58
$DG_2(MW)$	13.89
$STATCOM_{30}$ (MVAr)	35.78
$STATCOM_{29}$ (MVAr)	28.22
$STATCOM_{26}$ (MVAr)	28.21

30-bus are shown in Table 5.12.

TABLE 5.11: Optimal results for particular parameters at peak loading for IEEE 30 bus system

$CMIindex$	Without DG & STATCOM	3.85
	With DG & STATCOM	20.3384
L_{index}	Without DG & STATCOM	0.2516
	With DG & STATCOM	0.1527
μ^{CMI}		0.9452
μ^{L}		0.86
μ^{F}		0.9016

From the Table 5.12, it is observed that the proposed fuzzified Taguchi method of identifying optimum sizing of DGs and STATCOMs delivers the best conceded solution among the chosen objectives. The overall degree of satisfaction of the proposed method is 0.8669 which is much higher than achieved by single objective alone.

Fig. 5.8 depicts the bus voltage profiles of load buses of the system. It can be seen that after the coordination of DGs and STATCOMs, the voltage profile of the system seems to be much more than without coordination. Moreover, there is noticeable improvement in voltage stability margin as L-index of all the load buses of case-C, as shown in Fig. 5.9, are found to be much lower than without coordination.

TABLE 5.12: Comparison of degree of satisfaction at peak loading for IEEE 30 bus system

Particulars	Only DGs	Only STATCOMs	Multi-objective coordination of DGs and STATCOMs
Highest overall degree of satisfaction	0.5662	0.4970	0.9016

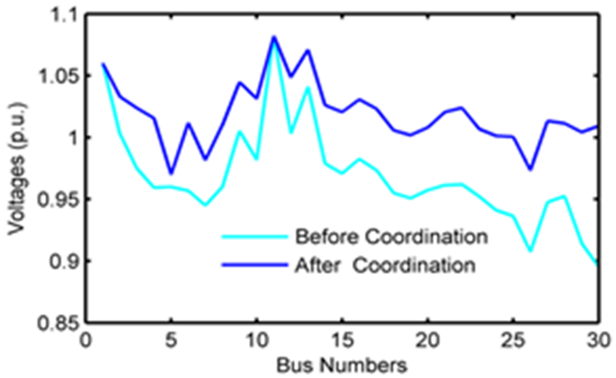


FIGURE 5.8: Voltage profile comparison before and after coordination

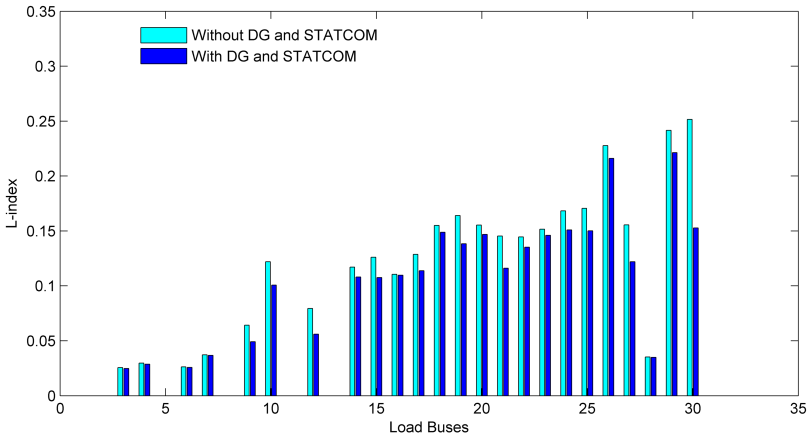


FIGURE 5.9: L-index comparison before and after coordination

The comparison of different parameters before and after coordination is shown in Table 5.13. It yields that the proposed coordination method is a quite superior in terms of higher membership function.

A comparison of state of congestion of transmission lines before and after optimal coordination is shown in Table 5.14. It is important to note from Table 5.14 that after

Table 5.13: Comparison of different parameters after coordination in IEEE 30 bus system

S.No	Devices	Proposed CMI index	L-index	P_{Loss} (MW)	Q_{Loss} (MVAr)	Membership Func.
1	Without DG & STATCOM	3.85	0.2516	47.808	139.581	–
2	Only DG	19.46	0.2104	32.6129	86.1628	0.5662
3	Only STATCOM	8.7085	0.1496	44.7164	130.9623	0.497
4	Both DG & STATCOM	20.3384	0.1527	29.4492	65.7559	0.9016

Table 5.14: Comparison of apparent power flow and congestion index before and after coordination

Branch (From-to)	MVA Limit	MVA flow before coordination	MVA flow after coordination	Proposed CMI index before coordination	Proposed CMI index after coordination
1-2	1.3	2.9722	1.061	-1.2863	0.1838
1-3	1.3	1.3542	1.0016	-0.0416	0.2295
2-4	0.65	1.2704	0.604	-0.9544	0.0707
3-4	1.3	1.2142	0.9261	0.066	0.2876
2-5	1.3	1.2704	1.029	0.0227	0.2084
2-6	0.65	0.6839	0.6099	-0.0521	0.0616
4-6	0.9	1.2142	0.8334	-0.3491	0.074
5-7	0.7	0.2934	0.2696	0.5808	0.6148
6-7	0.13	0.154	0.0251	-0.1846	0.8069
6-8	0.32	1.3542	0.3153	-3.2318	0.0146
6-9	0.65	0.4326	0.4104	0.3344	0.3686
6-10	0.32	0.3712	0.2291	-0.16	0.284
9-11	0.65	0.3712	0.1838	0.4289	0.7172
9-10	0.65	0.475	0.4071	0.2692	0.3736
4-12	0.65	0.9355	0.6316	-0.4392	0.0283
12-13	0.65	0.2712	0.1778	0.5827	0.7264
12-14	0.32	0.1252	0.1147	0.6087	0.6415
12-15	0.32	0.2934	0.2538	0.0831	0.2068
12-16	0.32	0.1207	0.0977	0.6228	0.6946
14-15	0.16	0.0272	0.0173	0.83	0.8918
16-17	0.16	0.0597	0.0397	0.6268	0.7518
15-18	0.16	0.094	0.0856	0.4125	0.465
18-19	0.16	0.2905	0.0357	-0.8156	0.7768
19-20	0.32	0.1078	0.117	0.6631	0.6343
10-20	0.32	0.1465	0.1558	0.5421	0.5131
10-17	0.32	0.1028	0.1277	0.6787	0.6009
10-21	0.32	0.2858	0.2121	0.1068	0.3371
10-22	0.32	0.1369	0.0985	0.5721	0.6921
21-22	0.32	0.0296	0.0965	0.9075	0.6984
15-23	0.16	0.0921	0.0561	0.4243	0.6493
22-24	0.16	0.1044	0.1097	0.3475	0.3143
23-24	0.16	0.0379	0.0132	0.7631	0.9175
24-25	0.16	0.0269	0.1057	0.8318	0.3393
25-26	0.16	0.0644	0.0641	0.5975	0.5993
25-27	0.16	0.07	0.1472	0.5625	0.08
28-27	0.65	0.2905	0.1305	0.553	0.7992
27-29	0.16	0.0978	0.0218	0.38875	0.8637
27-30	0.16	0.6836	0.0334	-3.2725	0.7912
29-30	0.16	0.0565	0.0358	0.6468	0.7762
8-28	0.32	0.02	0.0436	0.9375	0.8637
6-28	0.32	0.4326	0.1957	-0.3518	0.3884
			$\sum$	3.85	20.3384

coordination, congestion in the lines is fully alleviated and the voltage stability of the system is also enhanced.

On the basis of the results, it can be summarized that proposed fuzzified-TM is very effective for finding optimum sizing of DGs and STATCOMs for congestion management and voltage stability improvement.

5.4.2 IEEE 118 Bus Test System

The proposed method is also implemented on IEEE 118-bus system [153] to investigate its potential on large network. Based on CMI index, critical lines are identified. Thereafter, from critical lines, critical load buses are recognised for the placement of renewable DG. Besides this, TM is involved to identify optimal sizing of DGs for reducing congestion in the lines. Moreover, the effect of STATCOMs are also investigated to identify optimal sizing for enhancing voltage stability of the system. Afterwards role of both DGs and STATCOMs are investigated simultaenously to maximize CMI index and to improve voltage stability of the system. Application potential of different devices (DGs and STATCOMs) and their coordination has been investigated for peak loading (149% of base loading). Similar to IEEE 30-bus system, simulation study has been carried for three cases. Simulation results of these cases are discussed in the following sections:

- ***Case A: Investigation of DGs placement***

CMI index of different lines is calculated. The set of critical lines which are breaching their MVA limits are shown Fig 5.10. Based on critical lines obtained from Fig 5.10, critical load buses are recognised for the placement of DG. For the sake of clarity, only the most critical lines in the order of level of congestion is shown in Fig 5.10. Initially one DG is placed at the bus of CMI rank one and proposed index is calculated. Then another DG is placed at bus of CMI rank two and proposed index is calculated. The process is repeated with addition of DGs. Proposed index for different number of DGs are shown in Table 5.15. Form the table, it is significant to note that the optimal number of DG comes out to be seven. Beyond seven DGs, the CMI index reduces. DGs are placed on the buses in the order of CMI ranking. The maximum size of each DG is assumed to be 15 MW.

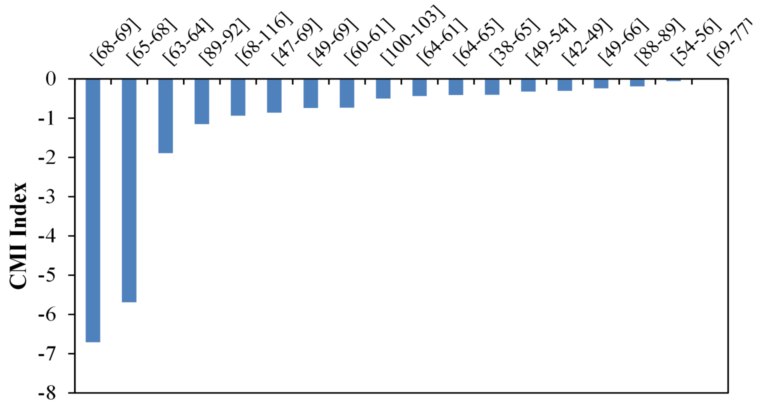


FIGURE 5.10: Congestion of weak buses at peak loading of IEEE 118 bus system.

TABLE 5.15: Comparative analysis of optimal quantity of DG for IEEE 118 bus

Parameter	Without DG	With single DG	With two DG	With three DG	With four DG	With five DG	With six DG	With seven DG	With eight DG
CMI Index	78.44	80.01	82.14	85.78	92.90	97.32	101.99	105.10	104.86

Effect of DGs for minimization of congestion in the lines is invetigated by proposed Taguchi based method. Therefore, fuzzy membership functions μ^{CMI} is selected as fitness function for maximization of CMI index. The simulation results are summarized in Table 5.16. The optimum sizing of obtained through TM is shown in Table 5.16. It has been observed from the table, that placement of DG on buses (68, 65, 89, 116, 47, 49, 60) increases the proposed CMI index from 78.44 to 105.10. L-index decreases marginally from 0.1065 to 0.0928.

TABLE 5.16: Optimal allocation of DGs for different objectives for IEEE 118 bus system

Objective Function	Locations (from-to bus)	Optimal Sizing (MW)	Results Comparison		
			Particulars	Without DG	With DG
$CMI Maximization$	68 65 89 116 47 49 60	7.26 14.82 11.50 5.05 8.10 13.83 13.19	CMI Index L-index	78.44 0.1065	105.10 0.0928

Results for minimization of congestion are presented in Table 5.16. The CMI index is significantly increased from 78.44 to 105.10 which indicate that placement of DGs is a most effective way of line congestion mitigation.

Role of DG is also investigated for voltage stability enhancement. The impact is observed in terms of L-index. As shown in Table 5.16, optimally placed DGs reduces the L-index marginally from 0.1065 to 0.0928. L-index of different buses before and after placement of DGs are shown in Fig. 5.11. It is observed from this fig that there is only a slight improvement in voltage stability margin as L-index of all the load buses after DGs placement is found to be slightly lower than without DG placement. Voltage profiles of different buses before and after DGs placement is shown in Fig. 5.12.

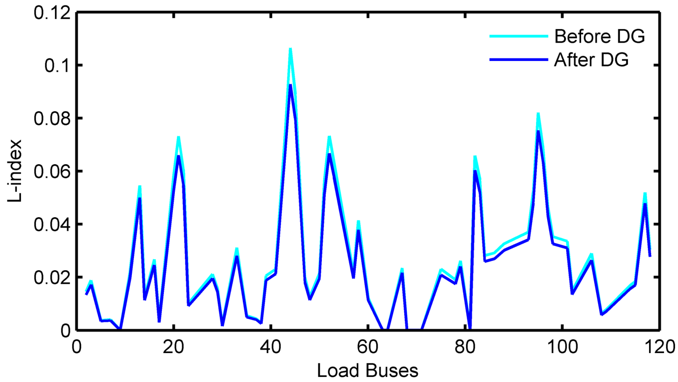


FIGURE 5.11: L-index comparison before and after DG

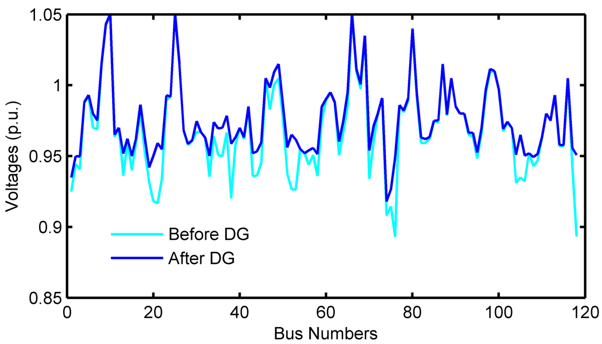


FIGURE 5.12: Voltage profile comparison before and after DG

- ***Case B: Investigation of placement of STATCOMs***

The effectiveness of STATCOM for improving voltage stability and minimizing congestion index is also investigated on larger bus system. The suitable locations for placement of STATCOMs are selected on the basis of L-index shown in Fig. 5.13 .

The number of STATCOMs for placement have also been estimated through L-index. The comparative study of L-index for different number of STATCOMs is shown in Table 5.17. Form this table it is observed that the L-index is almost same for three and four number of STATCOMs. Considering the cost of STATCOM, the optimal number of STATCOMs to be placed is selected as three. The sizing of each STATCOM is assumed to be of 50 MVAr.

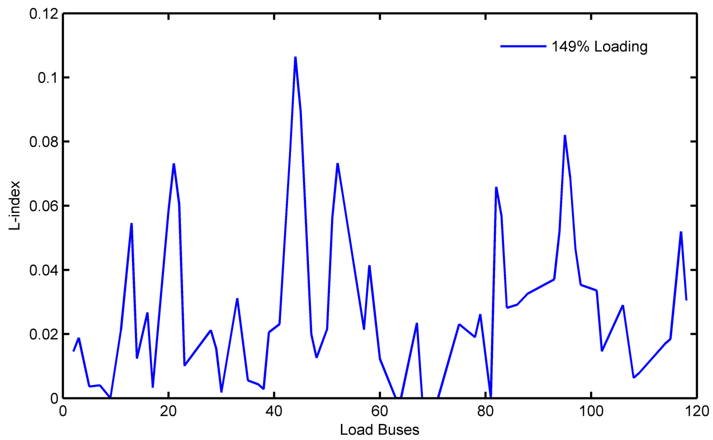


FIGURE 5.13: L-index of load buses at peak MVA loading for IEEE 118-bus

TABLE 5.17: Comparative study for optimal quantity of STATCOMs for IEEE 118 bus system

Parameter	Without STATCOM	With single STATCOM	With two STATCOM	With three STATCOM	With four STATCOM
L Index	0.1065	0.1050	0.1023	0.0776	0.0774

TABLE 5.18: Optimal allocation of STATCOMs for L-index minimization

Objective Function	Locations (from-to bus)	Optimal Sizing (MVAr)	Results Comparison		
			Particulars	Without Compensation	With Compensation
$L-indexMinimization$	44 45 95	47.78 25.81 16.33	CMI Index	78.44	97.52
			L-index	0.1065	0.0776

To see the impact of STATCOMs on voltage stability margin, fuzzy membership function μ_L is selected as fitness function for maximization in the proposed method. Higher value of μ_L is an indicator of minimization of L- index. The results of optimization are shown in Table 5.18. The L-index of the overall system is reduced from 0.1065 to 0.0776 which shows considerable improvement in voltage stability margin of the system. As shown in Fig. 5.14 , after placement of STATCOMs, L-index of the entire load buses are found to be lower than before compensation. Fig. 5.15 depicts the improved bus voltage profiles before and after compensation.

Results of IEEE 118-bus system support the findings of IEEE 30-bus system. On the basis of cases A and B of IEEE 118-bus system, it can be verified that DG is a better choice for alleviating congestion in lines while STATCOM is more effective for voltage stability improvement. Therefore, optimal coordinated placement of DGs and STATCOMs is the most effective approach for line congestion mitigation and voltage stability improvement. Proposed method is used to find the effect of coordinated placement of DGs and STATCOMs. The results of investigation are presented in the next section:

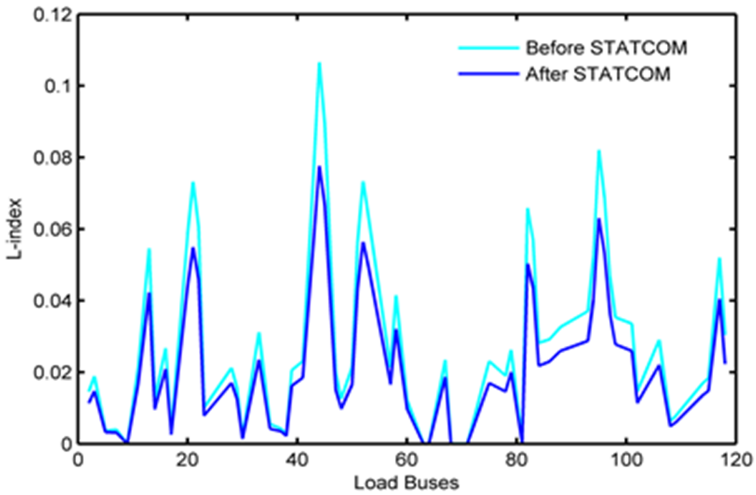


FIGURE 5.14: L-index comparison before and after STATCOM

- ***Case C: Investigation of coordinated placement of DGs and STATCOMs***

The efficiency of DG and STATCOM for selected objectives can be measured by converting multiple optimization problem into a single objective optimization problem through fuzzy approach. A trapezoidal fuzzy function has been used to find membership values of variables. Upper bound of CMI index and lower bound of L-index is chosen corresponding to base case value. The lower bound of CMI index and upper bound of

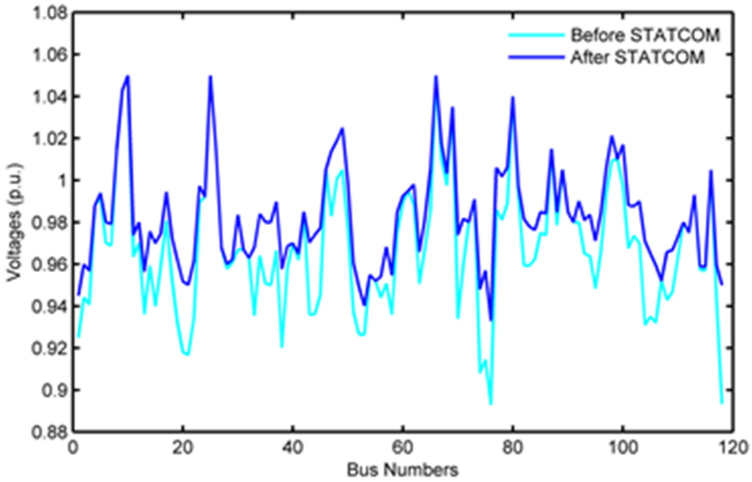


FIGURE 5.15: Voltage profile comparison before and after STATCOM

L-index is chosen from Table 5.18. The upper and lower limits of variables of different objectives are shown in Tables 5.19 and 5.20. The proposed multi-objective method has been applied on the system using the limiting values shown in Tables 5.19 and 5.20.

TABLE 5.19: Lower and upper bounds for CMI of IEEE 118 bus system

Objectives	Upper Bound	Lower Bound
CMI	119.90	78.84

TABLE 5.20: Lower and upper bounds for L-index of IEEE 118 bus system

Objectives	Lower Bound	Upper Bound
$L - index$	0.0684	0.1065

The results are summarized in Tables 5.22 and 5.23. The performance of cases A, B, and C is compared on the basis of overall fuzzy function. From the Table 5.23, it is observed that the overall degree of satisfaction of the case C is 0.7915 which is much higher than obtained for the cases A and B. It proves that the overall performance of the system can be improved remarkably with the optimal placement of DGs and STATCOMs using proposed method.

TABLE 5.21: Optimum location and sizing of DG and STATCOM after coordination

Parameters	Optimal Results
$DG_{68}(MW)$	14.28
$DG_{65}(MW)$	13.38
$DG_{89}(MW)$	13.91
$DG_{116}(MW)$	14.21
$DG_{47}(MW)$	11.56
$DG_{49}(MW)$	9.10
$DG_{60}(MW)$	12.56
$STATCOM_{44}(MVAr)$	47.81
$STATCOM_{45}(MVAr)$	26.45
$STATCOM_{95}(MVAr)$	18.45

TABLE 5.22: Optimal results for particular parameters at peak loading for IEEE 118 bus system

$CMIindex$	Without DG STATCOM	78.44
	With DG STATCOM	117.26
$L - index$	Without DG & STATCOM	0.1065
	With DG & STATCOM	0.081
μ^{CMI}		0.9363
μ^{L}		0.6692
μ^{F}		0.7915

Graphical comparison of voltage profile of the system and L-index of the buses before and after optimal placement of DGs and STATCOMs are presented in Figures 5.16 and 5.17. It again emphasizes the fact that proposed strategy is not only effective for line congestion but also improves voltage profile and voltage stability of the system.

TABLE 5.23: Comparison of degree of satisfaction for DGs and STATCOMs at IEEE 118 bus system

Particulars	Only DGs	Only STATCOMs	Multi-objective coordination of DGs and STATCOMs
Highest overall degree of satisfaction	0.4807	0.5908	0.7915

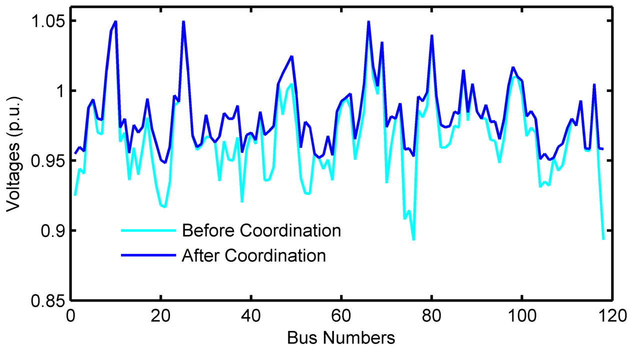


FIGURE 5.16: Voltage profile comparison before and after coordination

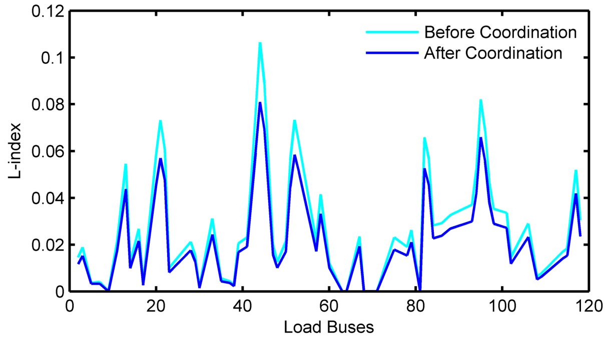


FIGURE 5.17: L-index comparison before and after coordination

5.5 Summary

Lack of expansion of transmission network due to environmental and other restriction have led to congestions in the existing transmission network with increase in load demand which may finally converges voltage instability. Congestion state of lines and voltage stability of the system can be improved by placing DGs and STATCOMs of optimal size at appropriate locations. In this chapter, a new congestion margin index (CMI) is proposed to measure the level of congestion in the transmission lines. DGs are placed on the basis of proposed CMI index and STATCOMs are placed on the basis of L-index. Sizing of DGs and STATCOMs are decided on the basis of a fuzzified Taguchi based method. The application potential of the proposed method for multi-objective formulation has been investigated on IEEE 30-bus and IEEE 118 bus systems. The following conclusions are drawn from this chapter:

1. Line congestion may lead to voltage instability. Proposed index is found to be a very effective tool to identify the congested line in the network. Negative value of the index for a line is an indication of overloading condition.

2. The optimal placement of DGs provide a most effective solution for congestion mitigation in the system although improvement in voltage stability is not much pronounced.

3. The optimal placement of STATCOMs is an effective means for voltage stability improvement. However, it is not suitable for mitigating line congestions.

4. The most competent solution among these objectives is obtained by simultaneous use of DGs and STATCOMs. Highest fitness value is attained through multiple devices (DGs and STATCOMs) on the basis of proposed strategy which implies highest degree of satisfaction among the selected objectives. Therefore, proposed fuzzified Taguchi based method is very effective for determining optimum sizing of DGs and STATCOMs.

Chapter 6

Conclusions

6.1 Important Findings

In this chapter, thesis contributions and important findings are highlighted; comparative analysis of voltage stability indices, identification of critical OLTCs and effect of allocation of DG and STATCOM on congestion management is presented. Major conclusions drawn from the research work are as under:

1. Voltage stability and voltage stability indices are more sensitive to reactive power flows than active power flows.
2. Lines which have high p.u. reactance are more prone to voltage stability problem.
3. Neglecting line resistance and shunt parameters of transmission system causes serious error in measurement of voltage stability status.
4. The proposed index is capable of predicting the PoC of the system very precisely and may be employed to monitor the voltage severity condition of all the lines and buses simultaneously both in offline and online mode.
5. Proposed index is mapped to compute the voltage stability margin in terms of MVA under various systems and operating conditions and accuracy is validated by comparing it with actual margin.

6. The new voltage stability index yields more realistic results as it depends upon transmission line ABCD parameters which accounts line charging capacitances and resistances.

7. Under heavy load conditions it is observed that some transformer loses their capability of raising the voltage with tap changing operation after certain tap ratio. Crucial transformer and its critical tap ratio are identified on the basis of proposed technique.

8. To cope up the problem of voltage instability owing to tap changing operation of OLTC, SVCs are installed. TM is employed to coordinate the tap changing operation of OLTC with SVC. Remarkable improvement in voltage stability is observed. Line losses are reduced and voltage profile of the system improved significantly.

9. The proposed coordination of OLTC and SVC approach through fuzzy based Taguchi method converges to better solutions in lesser time in comparison to the earlier approaches reported in literature.

10. An index is developed to measure the degree of congestion in lines and identifying the crucial transmission lines. DG units are placed to alleviate the excess load of the lines.

11. The optimum placement of DG provide a most viable solution for congestion mitigation and minimization of active/ reactive power loss of the system.

12. The placement of STATCOM is suitable for improving voltage stability, however, it is not effective for mitigating line congestions.

13. The integration of DGs and STATCOMs is found to be the most effective solution for reducing congestion and minimization of L-index. Moreover, the line losses are also reduced.

6.2 Major Contributions

The major contribution of the thesis work is outlined as follows:

1. The accuracy and consistency of existing voltage stability indices have been evaluated on standard IEEE test systems.

2. A simple and computationally efficient voltage stability index has been proposed to predict the occurrence of voltage collapse and translate the MVA margin of the system precisely.

3. An index has been proposed to predict the critical OLTCs. The proposed index is tested on standard IEEE bus systems under heavy loading conditions. Moreover, a new multi-objective fuzzified-Taguchi method has also been proposed to coordinate the OLTCs tappings and SVCs for improving voltage stability and decreasing line losses.

4. A new CMI index is developed which effectively identifies the congested lines. Moreover, a new multi-objective fuzzified-Taguchi method has been proposed to coordinate the DGs and STATCOMs. Proposed methodology for integration of DGs and STATCOMs into the system, effectively deals with the problem of congestion and improves voltage stability of the system.

6.3 Future Scope

The research work described in the thesis can be significant basis for future research activities related to assessment of voltage stability. Based on the research carried out in this thesis, the future research directions that appear from this thesis are summarized below:

1. The proposed index LVSI have been investigated on standard IEEE test systems. Further, it can also be used in online assessment of voltage stability. The proposed index may be employed on real power system for smooth and reliable operation of power systems.

2. The proposed index may be tested for its reliability for dynamic voltage stability. A relation can be derived between voltage sensitivity and proposed index.

3. The proposed index gives numerical value corresponding to the voltage stability. Numerical value of index LVSI can be used for monitoring the fault conditions and perilous condition of the lines.

4. The work on proposed index for critical transformer identification can be extended to find the congestion in the line. Moreover, integration of OLTC tappings with different FACTS devices can be utilized to cope up the problem of congestion and voltage instability.

5. A multi-objective formulation has been proposed in Chapter 5. The future work on the proposed method may include more objectives like cost, uncertainty etc. Different FACTS devices may also be considered for improving performance of power systems.

Appendix A

IEEE 30-bus Test System

This test transmission system and its data are referred from [153]. The data is on 100 MVA base.

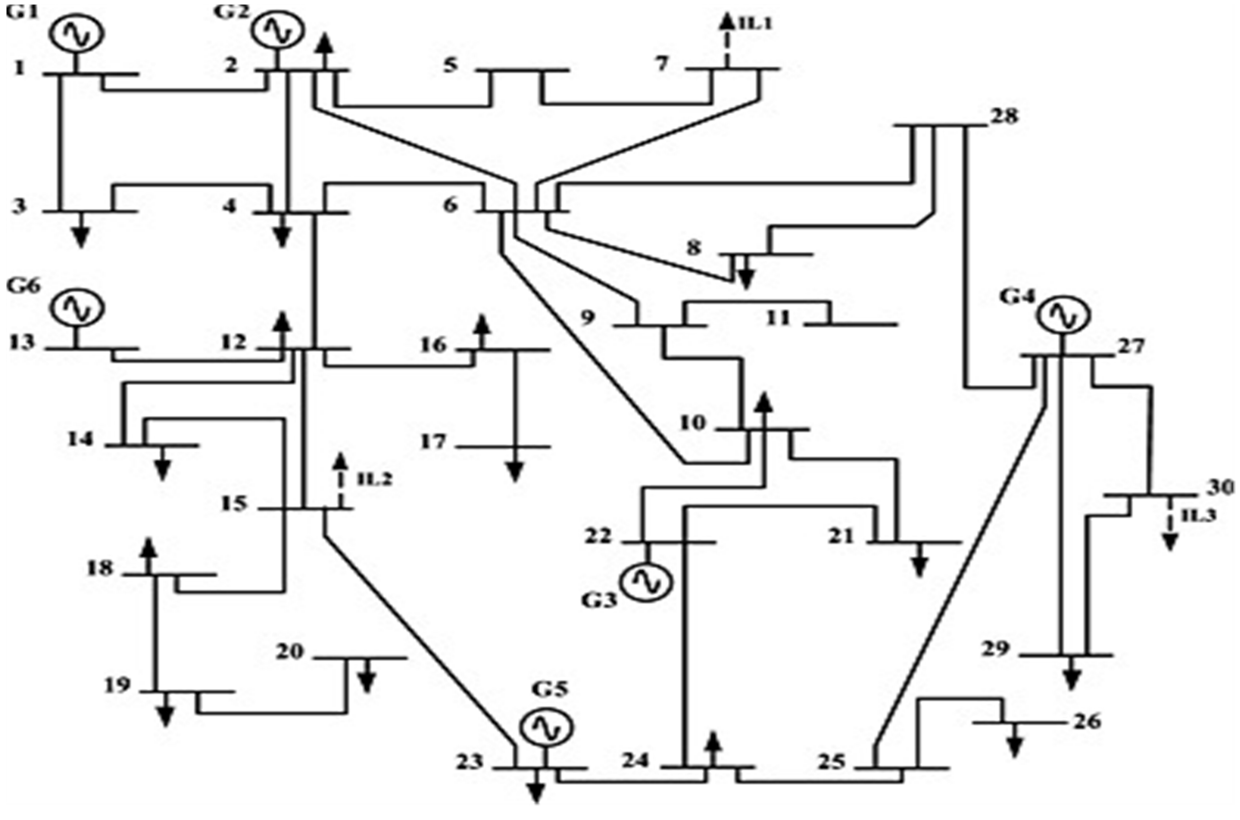


Figure A.1: IEEE 30 Bus Transmission System

Table A.1: IEEE 30 Bus Transmission System.

Bus No.	Bus Code	Volt (p.u.)	Ang. (deg.)	Load		Generator		Q_{min}	Q_{max}	Inj MVAr
				MW	MVAr	MW	MVAr			
1	1	1.06	0.00	0	0	0	0	0	0	0
2	2	1.04	-5.48	21.7	12.7	40	0	-40	50	0
3	0	1.03	-8.10	2.4	1.2	0	0	0	0	0
4	0	1.02	-9.77	7.6	1.6	0	0	0	0	0
5	2	1.01	-14.32	94.2	19	0	0	-40	40	0
6	0	1.02	-11.48	0	0	0	0	0	0	0
7	0	1.01	-13.17	22.8	10.9	0	0	0	0	0
8	2	1.01	-12.07	30	30	0	0	-10	60	0
9	0	1.00	-14.81	0	0	0	0	0	0	0
10	0	0.99	-16.47	5.8	2	0	0	-6	24	19
11	2	1.08	-14.81	0	0	0	0	0	0	0
12	0	1.02	-16.04	11.2	7.5	0	0	0	0	0
13	2	1.05	-16.04	0	0	0	0	-6	24	0
14	0	1.01	-16.97	6.2	1.6	0	0	0	0	0
15	0	1.00	-17.00	8.2	2.5	0	0	0	0	0
16	0	1.00	-16.50	3.5	1.8	0	0	0	0	0
17	0	0.99	-16.70	9	5.8	0	0	0	0	0
18	0	0.98	-17.57	3.2	0.9	0	0	0	0	0
19	0	0.98	-17.70	9.5	3.4	0	0	0	0	0
20	0	0.98	-17.45	2.2	0.7	0	0	0	0	0
21	0	0.98	-16.96	17.5	11.2	0	0	0	0	0
22	0	0.98	-16.95	0	0	0	0	0	0	0
23	0	0.99	-17.36	3.2	1.6	0	0	0	0	0
24	0	0.98	-17.47	8.7	6.7	0	0	0	0	4.3
25	0	1.00	-17.06	0	0	0	0	0	0	0
26	0	0.98	-17.49	3.5	2.3	0	0	0	0	0
27	0	1.02	-16.52	0	0	0	0	0	0	0
28	0	1.01	-12.13	0	0	0	0	0	0	0
29	0	1.00	-17.76	2.4	0.9	0	0	0	0	0
30	0	0.99	-18.65	10.6	1.9	0	0	0	0	0

0 - load bus

1 - slack bus

2 - generator bus

Table A.2: IEEE 30 Bus System Line Data.

Line No.	From Bus	To Bus	R (p.u.)	X (p.u.)	B (p.u.)	line code =1 for lines >1 or <1 for tr.tap
1	1	2	0.0192	0.0575	0.03	1
2	1	3	0.0452	0.1852	0.02	1
3	2	4	0.057	0.1737	0.02	1
4	3	4	0.0132	0.0379	0.00	1
5	2	5	0.0472	0.1983	0.02	1
6	2	6	0.0581	0.1763	0.02	1
7	4	6	0.0119	0.0414	0.00	1
8	5	7	0.046	0.116	0.01	1
9	6	7	0.0267	0.082	0.01	1
10	6	8	0.012	0.042	0.00	1
11	6	9	0	0.208	0.00	0.978
12	6	10	0	0.556	0.00	0.969
13	9	11	0	0.208	0.00	1
14	9	10	0	0.11	0.00	1
15	4	12	0	0.256	0.00	0.932
16	12	13	0	0.14	0.00	1
17	12	14	0.1231	0.2559	0.00	1
18	12	15	0.0662	0.1304	0.00	1
19	12	16	0.0945	0.1987	0.00	1
20	14	15	0.221	0.1997	0.00	1
21	16	17	0.0824	0.1923	0.00	1
22	15	18	0.1073	0.2185	0.00	1
23	18	19	0.0639	0.1292	0.00	1
24	19	20	0.034	0.068	0.00	1
25	10	20	0.0936	0.209	0.00	1
26	10	17	0.0324	0.0845	0.00	1

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27	10	21	0.0348	0.0749	0.00	1
28	10	22	0.0727	0.1499	0.00	1
29	21	22	0.0116	0.0236	0.00	1
30	15	23	0.1	0.202	0.00	1
31	22	24	0.115	0.179	0.00	1
32	23	24	0.132	0.27	0.00	1
33	24	25	0.1885	0.3292	0.00	1
34	25	26	0.2544	0.38	0.00	1
35	25	27	0.1093	0.2087	0.00	1
36	28	27	0	0.396	0.00	0.968
37	27	29	0.2198	0.4153	0.00	1
38	27	30	0.3202	0.6027	0.00	1
39	29	30	0.2399	0.4533	0.00	1
40	8	28	0.0636	0.2	0.02	1
41	6	28	0.0169	0.0599	0.07	1

Appendix B

IEEE 118-bus Test System

This test transmission system and its data are referred from [153]. The data is on 100 MVA base.

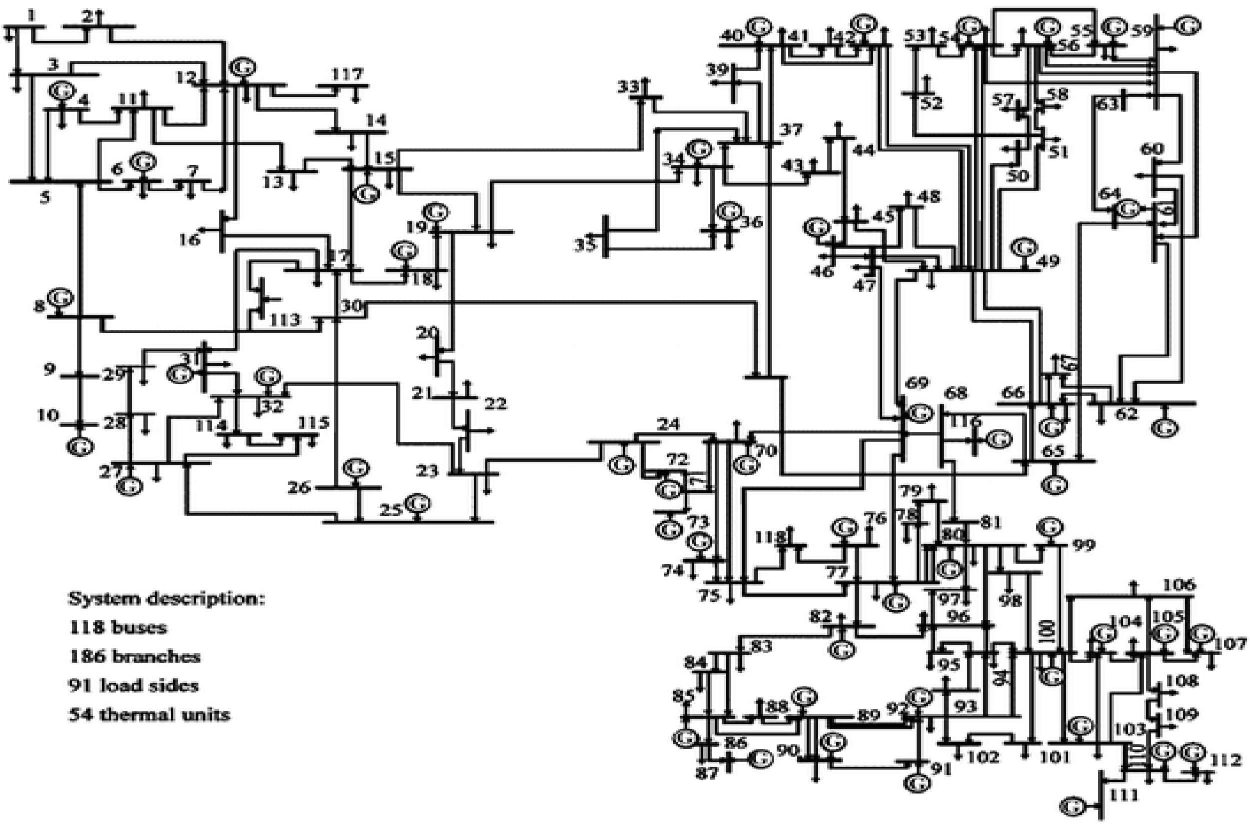

Figure B.1: IEEE 118 Bus Transmission System

Table B.1: IEEE 118 Bus Transmission System.

Bus No.	Bus Code	Volt (p.u.)	Ang. (deg.)	Load		Generator		Q_{min}	Q_{max}	Inj MVAr
				MW	MVAr	MW	MVAr			
69	1	0.96	-7.43	0	0	516.4	0	-300	300	0
2	0	0.97	-6.83	20	9	0	0	0	0	0
3	0	0.96	-6.45	39	10	0	0	0	0	0
4	2	0.99	-2.46	30	12	0	0	-300	300	0
5	0	0.99	-2.02	0	0	0	0	0	0	-40
6	2	0.98	-4.89	52	22	0	0	-13	50	0
7	0	0.98	-5.38	19	2	0	0	0	0	0
8	2	1.02	3.15	0	0	0	0	-300	300	0
9	0	1.04	10.41	0	0	0	0	0	0	0
10	2	1.05	17.99	0	0	450	0	-147	200	0
11	0	0.97	-5.22	70	23	0	0	0	0	0
12	2	0.98	-5.80	47	10	85	0	-35	120	0
13	0	0.96	-6.77	34	16	0	0	0	0	0
14	0	0.97	-6.68	14	1	0	0	0	0	0
15	2	0.96	-7.40	90	30	0	0	-10	30	0
16	0	0.97	-6.29	25	10	0	0	0	0	0
17	0	0.98	-4.84	11	3	0	0	0	0	0
18	2	0.96	-7.19	60	34	0	0	-16	50	0
19	2	0.96	-7.81	45	25	0	0	-8	24	0
20	0	0.96	-7.21	18	3	0	0	0	0	0
21	0	0.96	-5.82	14	8	0	0	0	0	0
22	0	0.97	-3.48	10	5	0	0	0	0	0
23	0	1.00	1.09	7	3	0	0	0	0	0
24	2	0.99	0.20	0	0	0	0	-300	300	0
25	2	1.04	8.71	0	0	220	0	-47	140	0
26	2	1.02	10.71	0	0	314	0	-1000	1000	0
27	2	0.97	-3.67	62	13	0	0	-300	300	0
28	0	0.96	-5.39	17	7	0	0	0	0	0
29	0	0.96	-6.39	24	4	0	0	0	0	0
30	0	1.02	0.30	0	0	0	0	0	0	0

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Bus No.	Bus Code	Volt (p.u.)	Ang. (deg.)	Load MW	Load MVAr	Generator MW	Generator MVAr	Q_{min}	Q_{max}	Inj MVAr
31	2	0.97	-6.27	43	27	7	0	-300	300	0
32	2	0.97	-4.52	59	23	0	0	-14	42	0
33	0	0.96	-8.06	23	9	0	0	0	0	0
34	2	0.98	-7.54	59	26	0	0	-8	24	14
35	0	0.98	-7.96	33	9	0	0	0	0	0
36	2	0.98	-7.97	31	17	0	0	-8	24	0
37	0	0.99	-6.97	0	0	0	0	0	0	-25
38	0	1.01	-2.42	0	0	0	0	0	0	0
39	0	0.97	-8.87	27	11	0	0	0	0	0
40	2	0.97	-9.09	20	23	0	0	-300	300	0
41	0	0.97	-9.58	37	10	0	0	0	0	0
42	2	0.99	-8.12	37	23	0	0	-300	300	0
43	0	0.97	-8.73	18	7	0	0	0	0	0
44	0	0.97	-7.88	16	8	0	0	0	0	0
45	0	0.98	-6.76	53	22	0	0	0	0	10
46	2	1.01	-4.69	28	10	19	0	-100	100	10
47	0	1.02	-3.23	34	0	0	0	0	0	0
48	0	1.02	-3.07	20	11	0	0	0	0	15
49	2	1.03	-2.03	87	30	204	0	-85	210	0
50	0	1.00	-4.12	17	4	0	0	0	0	0
51	0	0.97	-6.81	17	8	0	0	0	0	0
52	0	0.96	-7.78	18	5	0	0	0	0	0
53	0	0.95	-8.80	23	11	0	0	0	0	0
54	2	0.96	-7.93	113	32	48	0	-300	300	0
55	2	0.95	-8.23	63	22	0	0	-8	23	0
56	2	0.95	-8.04	84	18	0	0	-8	15	0
57	0	0.97	-6.76	12	3	0	0	0	0	0
58	0	0.96	-7.63	12	3	0	0	0	0	0
59	2	0.98	-3.82	277	113	155	0	-60	180	0
60	0	0.99	-0.14	78	3	0	0	0	0	0
61	2	1.00	0.74	0	0	160	0	-100	300	0
62	2	1.00	0.17	77	14	0	0	-20	20	0

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Bus No.	Bus Code	Volt (p.u.)	Ang. (deg.)	Load		Generator		Q_{min}	Q_{max}	Inj MVAr
				MW	MVAr	MW	MVAr			
63	0	1.06	-0.36	0	0	0	0	0	0	0
64	0	1.06	1.17	0	0	0	0	0	0	0
65	2	1.02	4.23	0	0	391	0	-67	200	0
66	2	1.07	4.08	39	18	392	0	-67	200	0
67	0	1.03	1.54	28	7	0	0	0	0	0
68	0	1.01	3.50	0	0	0	0	0	0	0
1	2	1.04	0.00	51	27	0	0	-5	15	0
70	2	0.99	-3.80	66	20	0	0	-10	32	0
71	0	0.99	-3.43	0	0	0	0	0	0	0
72	2	0.98	-1.53	0	0	0	0	-100	100	0
73	2	0.99	-3.42	0	0	0	0	-100	100	0
74	2	0.97	-5.01	68	27	0	0	-6	9	12
75	0	0.97	-3.79	47	11	0	0	0	0	0
76	2	0.94	-3.77	68	36	0	0	-8	23	0
77	2	1.00	2.92	61	28	0	0	-20	70	0
78	0	0.99	2.80	71	26	0	0	0	0	0
79	0	0.99	3.47	39	32	0	0	0	0	20
80	2	1.01	6.81	130	26	477	0	-165	280	0
81	0	1.05	4.47	0	0	0	0	0	0	0
82	0	0.98	6.80	54	27	0	0	0	0	20
83	0	0.98	8.94	20	10	0	0	0	0	10
84	0	0.98	12.98	11	7	0	0	0	0	0
85	2	0.99	15.25	24	15	0	0	-8	23	0
86	0	0.99	13.88	21	10	0	0	0	0	0
87	2	1.02	14.14	0	0	4	0	-100	1000	0
88	0	0.99	19.71	48	10	0	0	0	0	0
89	2	1.01	24.68	0	0	607	0	-210	300	0
90	2	0.99	21.03	78	42	0	0	-300	300	0
91	2	0.98	20.07	0	0	0	0	-100	100	0
92	2	1.00	18.16	65	10	0	0	-3	9	0
93	0	0.99	14.10	12	7	0	0	0	0	0
94	0	0.99	11.02	30	16	0	0	0	0	0

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Bus No.	Bus Code	Volt (p.u.)	Ang. (deg.)	Load		Generator		Q_{min}	Q_{max}	Inj MVAr
				MW	MVAr	MW	MVAr			
95	0	0.99	8.93	42	31	0	0	0	0	50
96	0	0.99	7.83	38	15	0	0	0	0	0
97	0	0.99	6.97	15	9	0	0	0	0	0
98	0	1.00	7.42	34	8	0	0	0	0	0
99	2	1.01	10.42	0	0	0	0	-100	100	0
100	2	1.02	11.75	37	18	252	0	-50	155	0
101	0	1.00	13.61	22	15	0	0	0	0	0
102	0	1.00	16.55	5	3	0	0	0	0	0
103	2	1.00	9.52	23	16	40	0	-15	40	0
104	2	0.98	7.06	38	25	0	0	-8	23	0
105	2	0.98	6.40	31	26	0	0	-8	23	20
106	0	0.97	6.10	43	16	0	0	0	0	0
107	2	0.95	4.86	28	12	0	0	-200	200	6
108	0	0.97	6.15	2	1	0	0	0	0	0
109	0	0.97	6.08	8	3	0	0	0	0	0
110	2	0.97	6.24	39	30	0	0	-8	23	6
111	2	0.98	7.89	0	0	36	0	-100	1000	0
112	2	0.98	5.08	25	13	0	0	-100	1000	0
113	2	0.99	-5.04	0	0	0	0	-100	200	0
114	0	0.97	-4.72	8	3	0	0	0	0	0
115	0	0.97	-4.71	22	7	0	0	0	0	0
116	2	1.01	3.50	0	0	0	0	-1000	1000	0
117	0	0.96	-7.37	20	8	0	0	0	0	0
118	0	0.95	-4.24	33	15	0	0	0	0	0

0 - load bus

1 - slack bus

2 - generator bus

Table B.2: IEEE 118 Bus System Line Data.

Line No.	From Bus	To Bus	R (p.u.)	X (p.u.)	B (p.u.)	line code =1 for lines >1 or <1 for tr.tap
1	1	2	0.0303	0.0999	0.0127	1
2	1	3	0.0129	0.0424	0.00541	1
3	4	5	0.00176	0.00798	0.00105	1
4	3	5	0.0241	0.108	0.0142	1
5	5	6	0.0119	0.054	0.00713	1
6	6	7	0.00459	0.0208	0.00275	1
7	8	9	0.00244	0.0305	0.581	1
8	8	5	0	0.0267	0	0.985
9	9	10	0.00258	0.0322	0.615	1
10	4	11	0.0209	0.0688	0.00874	1
11	5	11	0.0203	0.0682	0.00869	1
12	11	12	0.00595	0.0196	0.00251	1
13	2	12	0.0187	0.0616	0.00786	1
14	3	12	0.0484	0.16	0.0203	1
15	7	12	0.00862	0.034	0.00437	1
16	11	13	0.02225	0.0731	0.00938	1
17	12	14	0.0215	0.0707	0.00908	1
18	13	15	0.0744	0.2444	0.03134	1
19	14	15	0.0595	0.195	0.0251	1
20	12	16	0.0212	0.0834	0.0107	1
21	15	17	0.0132	0.0437	0.0222	1
22	16	17	0.0454	0.1801	0.0233	1
23	17	18	0.0123	0.0505	0.00649	1
24	18	19	0.01119	0.0493	0.00571	1
25	19	20	0.0252	0.117	0.0149	1
26	15	19	0.012	0.0394	0.00505	1
27	20	21	0.0183	0.0849	0.0108	1
28	21	22	0.0209	0.097	0.0123	1
29	22	23	0.0342	0.159	0.0202	1
30	23	24	0.0135	0.0492	0.0249	1

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31	23	25	0.0156	0.08	0.0432	1
32	26	25	0	0.0382	0	0.96
33	25	27	0.0318	0.163	0.0882	1
34	27	28	0.01913	0.0855	0.0108	1
35	28	29	0.0237	0.0943	0.0119	1
36	30	17	0	0.0388	0	0.96
37	8	30	0.00431	0.0504	0.257	1
38	26	30	0.00799	0.086	0.454	1
39	17	31	0.0474	0.1563	0.01995	1
40	29	31	0.0108	0.0331	0.00415	1
41	23	32	0.0317	0.1153	0.05865	1
42	31	32	0.0298	0.0985	0.01255	1
43	27	32	0.0229	0.0755	0.00963	1
44	15	33	0.038	0.1244	0.01597	1
45	19	34	0.0752	0.247	0.0316	1
46	35	36	0.00224	0.0102	0.00134	1
47	35	37	0.011	0.0497	0.00659	1
48	33	37	0.0415	0.142	0.0183	1
49	34	36	0.00871	0.0268	0.00284	1
50	34	37	0.00256	0.0094	0.00492	1
51	38	37	0	0.0375	0	0.935
52	37	39	0.0321	0.106	0.0135	1
53	37	40	0.0593	0.168	0.021	1
54	30	38	0.00464	0.054	0.211	1
55	39	40	0.0184	0.0605	0.00776	1
56	40	41	0.0145	0.0487	0.00611	1
57	40	42	0.0555	0.183	0.0233	1
58	41	42	0.041	0.135	0.0172	1
59	43	44	0.0608	0.2454	0.03034	1
60	34	43	0.0413	0.1681	0.02113	1
61	44	45	0.0224	0.0901	0.0112	1
62	45	46	0.04	0.1356	0.0166	1
63	46	47	0.038	0.127	0.0158	1
64	46	48	0.0601	0.189	0.0236	1

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65	47	49	0.0191	0.0625	0.00802	1
66	42	49	0.0357	0.1615	0.086	1
67	45	49	0.0684	0.186	0.0222	1
68	48	49	0.0179	0.0505	0.00629	1
69	49	50	0.0267	0.0752	0.00937	1
70	49	51	0.0486	0.137	0.0171	1
71	51	52	0.0203	0.0588	0.00698	1
72	52	53	0.0405	0.1635	0.02029	1
73	53	54	0.0263	0.122	0.0155	1
74	49	54	0.0399	0.1451	0.0734	1
75	54	55	0.0169	0.0707	0.0101	1
76	54	56	0.00275	0.00955	0.00366	1
77	55	56	0.00488	0.0151	0.00187	1
78	56	57	0.0343	0.0966	0.0121	1
79	50	57	0.0474	0.134	0.0166	1
80	56	58	0.0343	0.0966	0.0121	1
81	51	58	0.0255	0.0719	0.00894	1
82	54	59	0.0503	0.2293	0.0299	1
83	56	59	0.0407	0.1224	0.0553	1
84	55	59	0.04739	0.2158	0.02823	1
85	59	60	0.0317	0.145	0.0188	1
86	59	61	0.0328	0.15	0.0194	1
87	60	61	0.00264	0.0135	0.00728	1
88	60	62	0.0123	0.0561	0.00734	1
89	61	62	0.00824	0.0376	0.0049	1
90	63	59	0	0.0386	0	0.96
91	63	64	0.00172	0.02	0.108	1
92	64	61	0	0.0268	0	0.985
93	38	65	0.00901	0.0986	0.523	1
94	64	65	0.00269	0.0302	0.19	1
95	49	66	0.009	0.0459	0.0248	1
96	62	66	0.0482	0.218	0.0289	1
97	62	67	0.0258	0.117	0.0155	1
98	65	66	0	0.037	0	0.935

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99	66	67	0.0224	0.1015	0.01341	1
100	65	68	0.00138	0.016	0.319	1
101	47	69	0.0844	0.2778	0.03546	1
102	49	69	0.0985	0.324	0.0414	1
103	68	69	0	0.037	0	0.935
104	69	70	0.03	0.127	0.061	1
105	24	70	0.00221	0.4115	0.05099	1
106	70	71	0.00882	0.0355	0.00439	1
107	24	72	0.0488	0.196	0.0244	1
108	71	72	0.0446	0.18	0.02222	1
109	71	73	0.00866	0.0454	0.00589	1
110	70	74	0.0401	0.1323	0.01684	1
111	70	75	0.0428	0.141	0.018	1
112	69	75	0.0405	0.122	0.062	1
113	74	75	0.0123	0.0406	0.00517	1
114	76	77	0.0444	0.148	0.0184	1
115	69	77	0.0309	0.101	0.0519	1
116	75	77	0.0601	0.1999	0.02489	1
117	77	78	0.00376	0.0124	0.00632	1
118	78	79	0.00546	0.0244	0.00324	1
119	77	80	0.0109	0.0332	0.035	1
120	79	80	0.0156	0.0704	0.00935	1
121	68	81	0.00175	0.0202	0.404	1
122	81	80	0	0.037	0	0.935
123	77	82	0.0298	0.0853	0.04087	1
124	82	83	0.0112	0.03665	0.01898	1
125	83	84	0.0625	0.132	0.0129	1
126	83	85	0.043	0.148	0.0174	1
127	84	85	0.0302	0.0641	0.00617	1
128	85	86	0.035	0.123	0.0138	1
129	86	87	0.02828	0.2074	0.02225	1
130	85	88	0.02	0.102	0.0138	1
131	85	89	0.0239	0.173	0.0235	1
132	88	89	0.0139	0.0712	0.00967	1

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133	89	90	0.0164	0.0652	0.0794	1
134	90	91	0.0254	0.0836	0.0107	1
135	89	92	0.008	0.0383	0.0481	1
136	91	92	0.0387	0.1272	0.01634	1
137	92	93	0.0258	0.0848	0.0109	1
138	92	94	0.0481	0.158	0.0203	1
139	93	94	0.0223	0.0732	0.00938	1
140	94	95	0.0132	0.0434	0.00555	1
141	80	96	0.0356	0.182	0.0247	1
142	82	96	0.0162	0.053	0.0272	1
143	94	96	0.0269	0.0869	0.0115	1
144	80	97	0.0183	0.0934	0.0127	1
145	80	98	0.0238	0.108	0.0143	1
146	80	99	0.0454	0.206	0.0273	1
147	92	100	0.0648	0.295	0.0236	1
148	94	100	0.0178	0.058	0.0302	1
149	95	96	0.0171	0.0547	0.00737	1
150	96	97	0.0173	0.0885	0.012	1
151	98	100	0.0397	0.179	0.0238	1
152	99	100	0.018	0.0813	0.0108	1
153	100	101	0.0277	0.1262	0.0164	1
154	92	102	0.0123	0.0559	0.00732	1
155	101	102	0.0246	0.112	0.0147	1
156	100	103	0.016	0.0525	0.0268	1
157	100	104	0.0451	0.204	0.02705	1
158	103	104	0.0466	0.1584	0.02035	1
159	103	105	0.0535	0.1625	0.0204	1
160	100	106	0.0605	0.229	0.031	1
161	104	105	0.00994	0.0378	0.00493	1
162	105	106	0.014	0.0547	0.00717	1
163	105	107	0.053	0.183	0.0236	1
164	105	108	0.0261	0.0703	0.00922	1
165	106	107	0.053	0.183	0.0236	1
166	108	109	0.0105	0.0288	0.0038	1

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167	103	110	0.03906	0.1813	0.02305	1
168	109	110	0.0278	0.0762	0.0101	1
169	110	111	0.022	0.0755	0.01	1
170	110	112	0.0247	0.064	0.031	1
171	17	113	0.00913	0.0301	0.00384	1
172	32	113	0.0615	0.203	0.0259	1
173	32	114	0.0135	0.0612	0.00814	1
174	27	115	0.0164	0.0741	0.00986	1
175	114	115	0.0023	0.0104	0.00138	1
176	68	116	0.00034	0.00405	0.082	1
177	12	117	0.0329	0.14	0.0179	1
178	75	118	0.0145	0.0481	0.00599	1
179	76	118	0.0164	0.0544	0.00678	1

Appendix C

Publications

(A) Following papers have been accepted/published/revised for publication out of this thesis work:

International Journals

(a) Saurabh Ratra, Rajive Tiwari, K.R.Niazi, "Voltage stability assessment in power systems using line voltage stability index", **Computers and Electrical Engineering Journal, Elsevier,** Vol. 70, pp. 199-211, 2018.

(b) Saurabh Ratra, Rajive Tiwari, K.R.Niazi, "Voltage stability enhancement by the coordinated operation of OLTCs in the presence of wind turbines using taguchi method", **The Journal of Engineering, IET RPG,** Vol. 2017, pp. 1499-1504, 2017.

(c) Saurabh Ratra, Pradeep Singh, Rajive Tiwari, "Optimal placement of thyristor controlled series compensators for sensitive nodes in transmission system using voltage power sensitivity index" **International Journal of Electrical Engineering,** Vol. 4, No. 4, pp. 194-198, 2016.

(d) Saurabh Ratra, Jyotsna Singh, Rajive Tiwari, K.R.Niazi, "An analytical approach to find optimal location and sizing of DGs for power loss reduction and voltage stability improvement", **International Journal of Electrical Engineering,** Vol. 4, No. 4, pp. 189-193, 2016.

International Conferences

(a) Saurabh Ratra, Rajive Tiwari, "Artificial bee colony based optimal allocation of micro-turbines for voltage stability improvement of distribution systems", **IEEE Conference, ACEPT 2017,** Singapore, $24^{th} - 26^{th}$ October, 2017.

(b) Saurabh Ratra, Pradeep Singh, Rajive Tiwari, "Soft computing techniques for congestion management in power systems", **IEEE International Conference on Control and Energy Systems (ICPEICES)**, pp. 1-5, IEEE, $4^{th} - 6^{th}$ July 2016. .

(c) Saurabh Ratra, Pradeep Singh, Rajive Tiwari, "A novel approach for modelling of TCSC in load flow solution using NR and automatic differentiation", **India Conference (INDICON), 2015 Annual IEEE,** (pp. 1-6). IEEE, $15^{th} - 17^{th}$ December, 2015

(B) Following papers are under review for publication out of this thesis work:

International Journals

(a) Saurabh Ratra, Rajive Tiwari, K.R.Niazi,"Online and offline voltage collapse proximity estimation using line voltage stability index", **IET Generation, Transmission, Distribution.** I revision submitted.

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Biography

Author Biography

Saurabh Ratra received his B.E. (Hons.) degree from University of Rajasthan, Jaipur, India, and M.Tech degree from Punjab Technical University, Jalandhar, India. He is currently working toward the Ph.D. degree in the Department of Electrical Engineering, Malaviya National Institute of Technology, Jaipur, India.