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Impact of FACTS Devices on Zonal Congestion Management in Deregulated Power System

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Abstract

Congestion management is one of the most important issues for secure and reliable system operations in deregulated electricity market. In most cases, Independent System Operator tries to remove congestion by rescheduling output power of the generators. In this paper, transmission congestion distribution factors based on sensitivity of line real power have been proposed to identify the congestion clusters. The system operator can identify the generators from the most sensitive congestion clusters to reschedule their generation optimally to manage transmission congestion based on generator sensitivity efficiently. The role of thyristor controlled phase angle regulator and Thyristor controlled series Capacitor have been investigated for reducing the transmission congestion cost after locating it optimally in the system based on improved performance index. The effectiveness of the proposed method has been carried out on an IEEE 118 bus system and 62 bus Indian Utility System.
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Keywords: Congestion zones, Congestion Management, Transmission congestion distribution factors, Thyristor controlled phase angle regulator, Thyristor controlled series Capacitor, Rescheduling, Performance Index, and Sensitivity Index.

1. Introduction

Electric power systems, around the world, have been forced to operate to almost their full capacities due to the environmental and/or economic constraints to build new generating plants and transmission lines. This will lead to transmission systems functioning closer to their operating limits and cause increased congestion. Power flow in the lines and transformers should not be allowed to increase to a level where a random event could cause the network collapse because of angular instability, voltage instability or cascaded outages. When such a limit reaches, the system is said to be congested.

Transmission congestion (A.Fattahi 2007) can be defined as the condition where more power is scheduled to flows across transmission lines and transformers than the physical limits of those lines. Transmission congestion may prevent the existence of new contracts, lead to additional outages and increase the electricity prices in some regions of the electricity markets. A fast relief of congestion may be possible by removing congested lines to prevent severe damages to the system. To manage transmission congestion, we may initially establish rules for managing the market condition and preventing congestion from developing. FACTS devices may play an important role in a deregulated environment where line flows can be controlled to relieve congestion and real power losses can be minimized. To manage the congestion in real time operations, normally, following methods are adopted:

- Use of available resources for congestion management such as operation of FACTS controllers, rescheduling of generation based on minimum bids, etc.

- Provide the timely information regarding the probability of having a particular line congested and economic incentives to system users to adjust their requests and remain within the system constraints.

System operators (SO) always try to use first option, wherever (Roberto Mendez 2004) it is possible. Physical curtailment of loads is considered as the last option for congestion management when it is impossible to wait for the system users to respond according to economic criteria. However, the second option should be developed for giving the system users sufficient information regarding the congestion probability so that they can adjust their requests for system services and avoid congestion.
However, none of the methods discussed above provides the strategies to SO regarding the specific generators to be rescheduled or the loads to be curtailed for the congestion management.
A congestion clusters based method that identifies (H.Y.Yamina 2003) the groups of system users, which have a similar effect on a transmission constraint of interest. These cluster based on congestion distribution factors are termed as clusters of types 1, 2 and higher, where type 1 cluster represents users with strongest and non-uniform effects on transmission constraints of interest. The proposed clustering based method has been used to create an efficient congestion management market, where the transactions in the most sensitive cluster can help in eliminating congestion (Chien 1999). However, the method is based on dc load flow, which is based on the assumptions of lossless system with unit voltage at all the buses.
Flexible AC Transmission System (FACTS) controllers play an important role in increasing loadability of the existing system and controlling the congestion in the network. In this paper, a sensitivity based approach for the optimal location of thyristor controlled series capacitor (TCSC) and thyristor controlled phase angle regulator (TCPAR) was proposed for the congestion management. The optimal location of the controller has been decided based on modified performance index. The proposed method has been demonstrated on an IEEE 118 Bus system and 62 bus Indian Utility system.

2. Mathematical Formulation

2.1 Line Model with Thyristor Controlled Series Capacitor (TCSC)

Transmission lines are represented by lumped π equivalent parameters. The series compensator TCSC is simply a (seyed 2008) static capacitor with impedance $-jx_c$. The controllable reactance x_c is directly used as the control variable in the power flow equations
Figure1 shows a transmission line incorporating a TCSC. The Figure1.a shows a simple transmission line represented by its lumped π equivalent parameters connected between bus-i and bus-j.
Let complex voltage at bus-i and bus-j are $V_i\angle\delta_i$ and $V_j\angle\delta_j$ respectively. The real and reactive power flow from bus-i to bus-j can be written as

$$P_{ij} = V_i^2 G_{ij} - V_i V_j\left[G_{ij}\cos(\delta_{ij}) + B_{ij}\sin(\delta_{ij})\right] \quad (1)$$

$$Q_{ij} = -V_i^2(B_{ij} + B_{sh}) - V_i V_j\left[G_{ij}\sin(\delta_{ij}) - B_{ij}\cos(\delta_{ij})\right] \quad (2)$$

Similarly the real and reactive power flow from bus-j to bus-i can be written as

$$P_{ji} = V_j^2 G_{ij} - V_i V_j[G_{ij}\cos(\delta_{ij}) - B_{ij}\sin(\delta_{ij})] \quad (3)$$

$$Q_{ij} = -V_j^2(B_{ij} + B_{sh}) + V_i V_j\left[G_{ij}\sin(\delta_{ij}) + B_{ij}\cos(\delta_{ij})\right] \quad (4)$$

The active and reactive power losses in the line are

$$P_L = P_{ij} + P_{ji} = G_{ij}(V_i^2 + V_j^2) - 2V_i V_j G_{ij}\cos\delta_{ij} \quad (5)$$

$$Q_L = Q_{ij} + Q_{ji} = -(V_i^2 + V_j^2)(B_{ij} + B_{sh}) + 2V_i V_j G_{ij}\cos\delta_{ij} \quad (6)$$

The model of transmission line with a TCSC connected between bus-i and bus-j is shown in Figure1.b.
During the steady state the TCSC can be considered as a static reactance $-jx_c$. The real and reactive power flow from bus-i to bus-j and from bus-j to bus-i of a line having series impedance and a series reactance are

$$P_{ij}^{'} = V_i^2 G_{ij}^{'} - V_i V_j \left[G_{ij}^{'} \cos\left(\delta_{ij}\right) + B_{ij}^{'} \sin(\delta_{ij})\right] \quad (7)$$

$$Q_{ij}^{'} = -V_i^2 (B_{ij}^{'} + B_{sh}) - V_i V_j \left[G_{ij}^{'} \sin\left(\delta_{ij}\right) - B_{ij}^{'} \cos(\delta_{ij})\right] \quad (8)$$

$$P_{ji}^{'} = V_j^2 G_{ij}^{'} - V_i V_j [G_{ij}^{'} \cos(\delta_{ij}) - B_{ij}^{'} \sin(\delta_{ij})] \quad (9)$$

$$Q_{ij}^{'} = -V_j^2 (B_{ij}^{'} + B_{sh}) + V_i V_j \left[G_{ij}^{'} \sin\left(\delta_{ij}\right) + B_{ij}^{'} \cos(\delta_{ij})\right] \quad (10)$$

The active and reactive power losses in the line with TCSC are

$$P_L^{'} = P_{ij}^{'} + P_{ji}^{'} = G_{ij}^{'} (V_i^2 + V_j^2) - 2 V_i V_j G_{ij}^{'} \cos \delta_{ij} \quad (11)$$

$$Q_L^{'} = Q_{ij}^{'} + Q_{ji}^{'} = -(V_i^2 + V_j^2)(B_{ij}^{'} + B_{sh}) + 2 V_i V_j G_{ij}^{'} \cos \delta_{ij} \quad (12)$$

The change in the line flow due to series capacitance can be represented as a line without series capacitance with power injected at the receiving and sending ends of the line as shown in Figure1.c.

The real and reactive power injections at bus-i and bus-j can be expressed as

$$P_i^{'} = V_i^2 \Delta G_{ij} - V_i V_j \left[\Delta G_{ij} \cos\left(\delta_{ij}\right) + \Delta B_{ij} \sin(\delta_{ij})\right] \quad (13)$$

$$Q_i^{'} = -V_i^2 (\Delta B_{ij} + B_{sh}) - V_i V_j \left[\Delta G_{ij} \sin\left(\delta_{ij}\right) - \Delta B_{ij} \cos(\delta_{ij})\right] \quad (14)$$

Similarly, the real and reactive power injections at bus-j and bus-i can be expressed as

$$P_j^{'} = V_j^2 \Delta G_{ij} - V_i V_j [\Delta G_{ij} \cos(\delta_{ij}) - \Delta B_{ij} \sin(\delta_{ij})] \quad (15)$$

$$Q_j^{'} = -V_j^2 (\Delta B_{ij} + B_{sh}) + V_i V_j \left[\Delta G_{ij} \sin\left(\delta_{ij}\right) + \Delta B_{ij} \cos(\delta_{ij})\right] \quad (16)$$

2.2 Line Model with Thyristor Controlled Phase Angle Regulator (TCPAR)

In a thyristor-controlled phase angle regulator, the phase shift is achieved by introducing a variable voltage component in perpendicular to the phase voltage of the line. The static model of a TCPAR having a complex tap ratio of $1 : a\angle\alpha$ and a transmission line between bus i and bus j is shown in Fig.2.a

The real and reactive power flows from bus *i* to bus *j* can be expressed as

$$P_{ij} = a^2 V_i^2 G_{ij} - a V_i V_j G_{ij} \cos(\delta_i - \delta_j + \alpha) - a V_i V_j B_{ij} \sin(\delta_i - \delta_j + \alpha) \quad (17)$$

$$Q_{ij} = -a^2 V_i^2 B_{ij} + a V_i V_j B_{ij} \cos(\delta_i - \delta_j + \alpha) - a V_i V_j G_{ij} \sin(\delta_i - \delta_j + \alpha) \quad (18)$$

Similarly, real and reactive power flows from bus j to bus i can be written as

$$P_{ji} = V_j^2 G_{ij} - a V_i V_j G_{ij} \cos(\delta_i - \delta_j + \alpha) + a V_i V_j B_{ij} \sin(\delta_i - \delta_j + \alpha) \quad (19)$$

$$Q_{ji} = -V_j^2 B_{ij} - a V_i V_j B_{ij} \cos(\delta_i - \delta_j + \alpha) + a V_i V_j G_{ij} \sin(\delta_i - \delta_j + \alpha) \quad (20)$$

The real and reactive power loss in the line having a TCPAR can be expressed as

$$P_L = a^2 V_i^2 G_{ij} + V_j^2 G_{ij} - 2 a V_i V_j G_{ij} \cos(\delta_i - \delta_j + \alpha) \quad (21)$$

$$Q_L = -a^2 V_i^2 B_{ij} - V_j^2 B_{ij} + a V_i V_j B_{ij} \cos(\delta_i - \delta_j + \alpha) \quad (22)$$

The power injected at the receiving and sending ends of the line as shown in Figure2.b. The real and reactive power injections at bus-i and bus-j can be expressed as

$$P_i^{'} = -a^2 V_i^2 G_{ij} - a V_i V_j \left[G_{ij} \sin\left(\delta_{ij}\right) - B_{ij} \cos(\delta_{ij})\right] \quad (23)$$

$$Q_i^{'} = a^2 V_i^2 B_{ij} + a V_i V_j \left[G_{ij} \cos\left(\delta_{ij}\right) + B_{ij} \sin(\delta_{ij})\right] \quad (24)$$

Similarly, the real and reactive power injections at bus-j and bus-i can be expressed as

$$P_j^{'} = -a V_i V_j [G_{ij} \sin(\delta_{ij}) + B_{ij} \cos(\delta_{ij})] \quad (25)$$

$$Q_j^{'} = -a V_i V_j \left[G_{ij} \cos\left(\delta_{ij}\right) - B_{ij} \sin(\delta_{ij})\right] \quad (26)$$

2.3 Transmission congestion distribution factors

Transmission congestion distribution factors are defined as the change in real power flow(Ashwani 2004) in a transmission line-*k* connected between bus-*i* and bus-*j* due to unit change in the power injection (P_i) at bus-*i*. Mathematically, TCDF for line-*k* can be written as:

$$TCDF_i^k = \frac{\Delta P_{ij}}{\Delta P_i} \quad (27)$$

where Pij is the change in real power flow of line-*k*.

$TCDF_n^k$ denotes that how much active power flow over a transmission line connecting bus-*i* and bus-*j* would change due to active power injection at bus-*n*.

The real power flow ($P_{i,j}$) in a line-*k* connected between bus-*i* and bus-*j* can be written as:

$$P_{ij} = V_i V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) - V_i^2 Y_{ij} \cos\theta_{ij} \tag{28}$$

Using Taylor's series approximation and ignoring higher order terms, Eq. (28) can be written as:

$$\Delta P_{ij} = \frac{\partial P_{ij}}{\partial \delta_i}\Delta\delta_i + \frac{\partial P_{ij}}{\partial \delta_j}\Delta\delta_j + \frac{\partial P_{ij}}{\partial V_i}\Delta V_i + \frac{\partial P_{ij}}{\partial V_j}\Delta V_j \tag{29}$$

Eq. (29) can be rewritten as:

$$\Delta P_{ij} = a_{ij}\Delta\delta_i + b_{ij}\Delta\delta_j + c_{ij}\Delta V_i + d_{ij}\Delta V_j \tag{30}$$

The coefficients appearing in Eq. (30) can be obtained using the partial derivatives of real power flow Eq. (28) with respect to variables δ and V as:

$$a_{ij} = V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) \tag{31}$$

$$b_{ij} = -V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) \tag{32}$$

$$c_{ij} = V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) - 2V_i Y_{ij} \cos\theta_{ij} \tag{33}$$

$$d_{ij} = V_i Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) \tag{34}$$

For determination of TCDFs the following Jacobian relationship has been used

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = [J]\begin{bmatrix}\Delta\delta\\ \Delta V\end{bmatrix} = \begin{bmatrix}J_{11} & J_{12}\\ J_{21} & J_{22}\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta V\end{bmatrix} \tag{35}$$

Neglecting coupling between ΔP and ΔV and between ΔQ and $\Delta\delta$, Eq. (35) can be simplified as:

$$\Delta P = [J_{11}][\Delta\delta] \tag{36}$$

From Eq. (36), we get:

$$\Delta\delta = [J_{11}]^{-1}[\Delta P] = [M][\Delta P] \tag{37}$$

Eq. (37) can be written in the form:

$$\Delta\delta_i = \sum_{l=1}^{n} m_{il}\Delta P_l \qquad\qquad i = 1,2,....n, i \neq s \tag{38}$$

where *n* is the number of buses in the system and *s* is slack bus. It is assumed that the impact of change in the voltage on real power flow is negligible, and therefore, Eq. (30) can be written as:

$$\Delta P_{ij} = a_{ij}\Delta\delta_i + b_{ij}\Delta\delta_j \tag{39}$$

Substituting Eq. (38) into Eq. (39), we get:

$$\Delta P_{ij} = a_{ij}\sum_{l=1}^{n} m_{il}\Delta P_l + b_{ij}\sum_{l=1}^{n} m_{jl}\Delta P_l \tag{40}$$

$$\Delta P_{ij} = (a_{ij}m_{i1} + b_{ij}m_{j1})\Delta P_1 + (a_{ij}m_{i2} + b_{ij}m_{j2})\Delta P_2 + ... + (a_{ij}m_{in} + b_{ij}m_{jn})\Delta P_n \tag{41}$$

Therefore, change in the real power flow can be written as:

$$\Delta P_{ij} = TCDF_1^k \Delta P_1 + TCDF_2^k \Delta P_2 + ... + TCDF_n^k \Delta P_n \tag{42}$$

where $TCDF_n^k = (a_{ij}m_{in} + b_{ij}m_{jn})\Delta P_n$ are the transmission congestion distribution factors corresponding to bus-*n* for line-*k* connecting bus-*i* and bus-*j*.

3. Optimal Location of FACTS devices based on real power Performance Index

The severity of the system loading under normal and contingency cases can be described by a real power line flow performance index, as given below.

$$PI = \sum_{m=1}^{N_L} \frac{w_m}{2n}\left(\frac{P_{Lm}}{P_{Lm}^{\max}}\right)^{2n}$$

(43)

where P_{Lm} is the real power flow
$P_{Lm}^{\max}$ is the rated capacity of line-m,
n is the exponent and
w_m a real nonnegative weighting coefficient which may be used to reflect the importance of lines. will be small when all the lines are within their limits and reach a high value when there are overloads. Thus, it provides a good measure of severity of the line overloads for given state of the power system. Most of the works on contingency selection algorithms utilize the second order performance indices which, in general, suffer from masking effects. By most of the operational standards, the system with one huge violation is much more severe than that with many small violations. Masking effect to some extent can be avoided using higher order performance indices that are n > 1. However, in this study, the value of exponent has been taken as 2 and w_i =1.

3.1 Thyristor Controlled Series Capacitor (TCSC)

The real power flow PI sensitivity factors with respect to the parameters of TCSC can be defined as

$$b_k = \frac{\partial PI}{\partial x_{ck}}\Big|_{x_{ck}=0} \tag{44}$$

The sensitivity of PI with respect to TCSC parameter connected between bus-i and bus-j can be written as

$$\frac{\partial PI}{\partial x_{ck}} = \sum_{m=1}^{N_L} w_m P_{Lm}^3 \left(\frac{1}{P_{Lm}^{\max}}\right)^4 \frac{\partial P_{Lm}}{\partial x_{ck}} \tag{45}$$

The real power flow in a line-m can be represented in terms of real power injections using DC power flow equations where s is slack bus, as

$$P_{Lm} = \begin{cases} \sum\limits_{\substack{n=1\\ n\neq s}}^{N} S_{mn} P_n & for \quad m \neq k \\ \sum\limits_{\substack{n=1\\ n\neq s}}^{N} S_{mn} P_n + P_j & for \quad m = k \end{cases} \tag{46}$$

The terms $\frac{\partial P_i}{\partial x_{ck}}\big|_{x_{ck=0}}$ and $\frac{\partial P_j}{\partial x_{ck}}\big|_{x_{ck=0}}$ can be derived as below

$$\frac{\partial P_i}{\partial x_{ck}}\Big|_{x_{ck=0}} = \frac{\partial P'_i}{\partial x_{ck}}\Big|_{x_{ck=0}}$$

$$= -2(V_i^2 - V_iV_j\cos\delta_{ij})\frac{r_{ij}x_{ij}}{(r_{ij}^2 + x_{ij}^2)^2} - V_iV_j\sin\delta_{ij}\frac{(x_{ij}^2 - r_{ij}^2)}{(r_{ij}^2 + x_{ij}^2)^2} \tag{47}$$

$$\frac{\partial P_j}{\partial x_{ck}}\Big|_{x_{ck=0}} = \frac{\partial P'_j}{\partial x_{ck}}\Big|_{x_{ck}=0}$$

$$= -2(V_j^2 - V_iV_j\cos\delta_{ij})\frac{r_{ij}x_{ij}}{(r_{ij}^2 + x_{ij}^2)^2} + V_iV_j\sin\delta_{ij}\frac{(x_{ij}^2 - r_{ij}^2)}{(r_{ij}^2 + x_{ij}^2)^2} \tag{48}$$

Using PI method TCSC should be placed in a line having most negative Performance index.

3.2 Thyristor Controlled Phase Angle Regulator (TCPAR)

The real power flow PI sensitivity factors with respect to the parameters of TCPAR can be defined as

$$b_k = \frac{\partial PI}{\partial \alpha_k}\Big|_{\alpha_k=0} \tag{49}$$

The terms $\frac{\partial P_i}{\partial \alpha_k}|_{\alpha_{k=0}}$ and $\frac{\partial P_j}{\partial \alpha_k}|_{\alpha_{k=0}}$ can be derived as below

$$\frac{\partial P_i}{\partial \alpha_k}|_{\alpha_{k=0}} = \frac{\partial P'_i}{\partial \alpha_k}|_{\alpha_{k=0}} = V_i V_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}) \quad (50)$$

$$\frac{\partial P_j}{\partial x_{ck}}|_{x_{ck=0}} = \frac{\partial P'_j}{\partial x_{ck}}|_{x_{ck=0}} = -V_i V_j (G_{ij} \sin \delta_{ij} + B_{ij} \cos \delta_{ij}) \quad (51)$$

Using PI method TCPAR should be placed in the most sensitive line-*k* with a largest absolute value of the sensitivity index.

4. Congestion zone based transmission management in deregulated market

The TCDFs obtained based on the methodology discussed have been utilized (A. Kumar 2008) for identifying different congestion clusters (zones) for a given system. The congestion zone of type 1 is the one having large and non-uniform TCDFs and the congestion zones of type 2 and higher order have small or similar TCDFs. Therefore, the transactions in the congestion zone 1 have critical and unequal impact on the line flow. The congestion zones of types 2, 3 and higher are farther from the congested line of interest. Therefore, any transaction outside the most sensitive zone 1 will contribute very little to the line flow. Thus, the identification of congestion zones will reduce the effort of SO in selecting the participants for congestion management and that will also reduce the computation burden.

In this paper, based on the TCDFs, the SO identifies the most sensitive zones and optimally selects the generators for rescheduling based on real power generator Sensitivity factors (Elango 2011)in the sensitive zones for congestion management.

5. Results And Discussions

The Proposed concept of congestion zone based congestion management system utilizing the TCDFs is illustrated on an IEEE 118 Bus system and 62 bus Indian Utility system.

5.1 IEEE 118 Bus System

For this system the congestion clusters/zones based on the proposed method for a line of interest 8-5 are shown in Fig. 3. The congestion zones are decided on the basis of TCDFs and accordingly the SO selects most sensitive congestion zones for managing congestion. The most sensitive zone 1 is based on TCDFs, which are highly non-uniform and large in magnitude. The congestion zones of order 2 and higher comprise TCDFs of smaller magnitude with almost uniform variation.

The TCDFs for the congested line 8-5 corresponding to each bus are given in Table 1 for the four different zones. The zone 1 is the most sensitive zone with larger magnitude and strongest non-uniform distribution of TCDFs. The magnitudes of TCDFs in zone 4 are higher than zone 2 and zone 3 but due to uniform distribution of TCDFs, the zone 4 is least sensitive zone.

It is assumed that the generators G12 and G25 from most sensitive zones participate for congestion management based on the generator sensitivities. TCSC is located optimally at two locations on line 90-91 and line 100-101 with 70% and 20% of line reactance respectively from the sensitivity based approach. The performance index for this line is found to be maximum. TCPAR is located optimally on congested line 11-12 from the sensitivity based approach.

The congestion costs with and without FACTS are presented in Table 2 and Fig. 4. Fig.5 gives the comparison of re-scheduled generation for all generators without and with FACTS. From Fig. 4, it is observed that TCSC located optimally in the system is highly effective in reducing the congestion cost. From Fig.5, it is found that the generators are subjected to lower magnitude of rescheduling in the presence of TCSC.

5.2 62 bus Indian Utility System

For this system the congestion clusters/zones based on the proposed method for a line of interest 48-47 are shown in Fig. 6.

The TCDFs for the congested line 48-47 corresponding to each bus are given in Table 3 for the three different zones. The zone 1 is the most sensitive zone with larger magnitude and strongest non-uniform distribution of TCDFs. The magnitudes of TCDFs in zone 3 are higher than zone 2 but due to uniform distribution of TCDFs, the zone 3 is least sensitive zone.

It is assumed that the generators G49 and G50 from most sensitive zones participate for congestion management based on the generator sensitivities. TCSC is located optimally at two locations on line 40-30 and line 12-13 with 70% and 20% of line reactance respectively from the sensitivity based approach. The performance index for this line is found to be maximum. TCPAR is located optimally on congested line 48-50 from the sensitivity based approach.

The congestion costs with and without FACTS are presented in Table 4 and Fig. 7. Fig.8 gives the comparison of re-scheduled generation for all generators without and with FACTS. From Fig. 7, it is observed that TCSC located optimally in the system is highly effective in reducing the congestion cost. From Fig.8, it is found that the generators are subjected to lower magnitude of rescheduling in the presence of TCSC.

6. Conclusions

This paper proposes a simple and efficient congestion management method based on congestion zones/clusters obtained with new set of transmission congestion distribution factors. The optimal location of TCSC and TCPAR have been determined based on improved performance index and its impact on congestion cost reduction has also been studied. TCSC reduces considerably the generation re-dispatch, and the congestion cost compared to TCPAR. The market administrator can post the information of congested zones/clusters so that the market participants can bid and adjust their outputs for congestion management, accordingly. The optimal deployment of phase shifters can help to manage congestion effectively.

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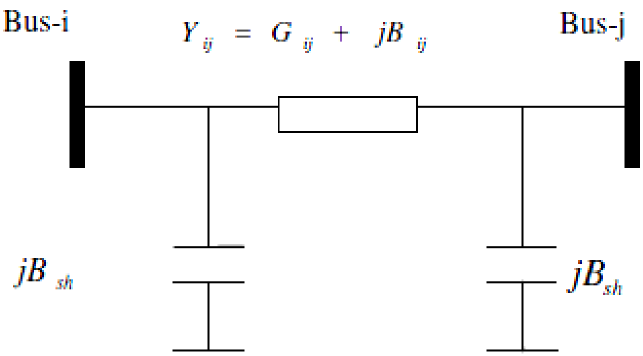
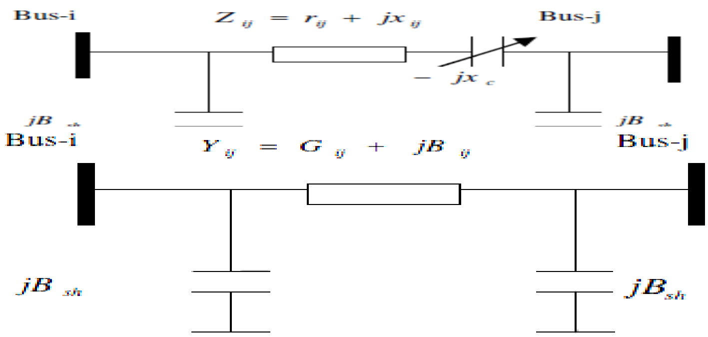


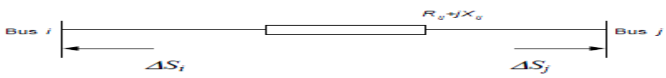
er Systems) from Andhra University,
Dynamics in Power Systems from IISc,
ngineer, he joined on the Teaching Faculty
and served for more than 40 years in
resently working as a Senior Professor in
a total service of over 53 years. To his
onferences and Journals of National and

overnment. His research interests are in
Voltage Stability and Reactive power

1(a) Simple Transmission line



2(a) Model of TCPAR



2(b) Injected model of TCPAR

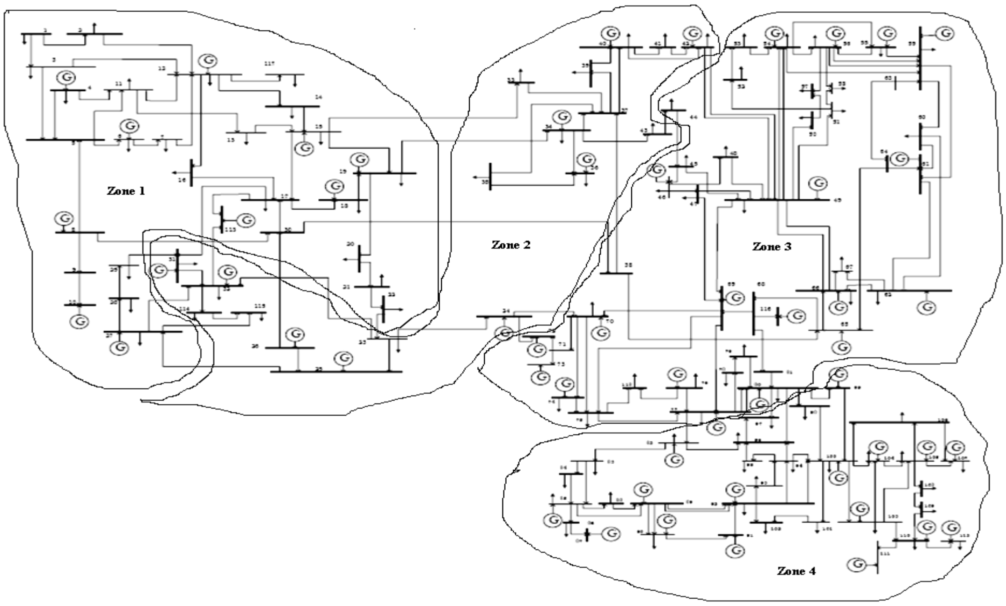


Fig.3 Congestion Zones for 118 Bus System

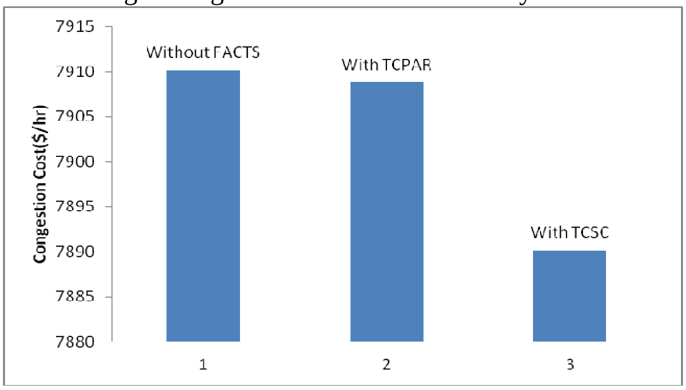


Fig.4 Congestion Cost for 118 Bus System without and with FACTS

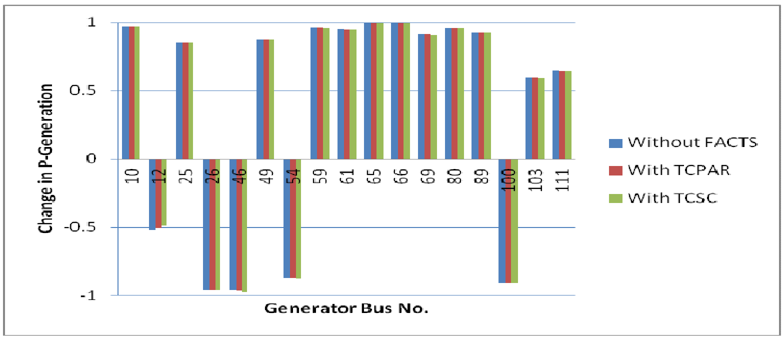


Fig.5 Change in P-Generation for 118 Bus System without and with FACTS

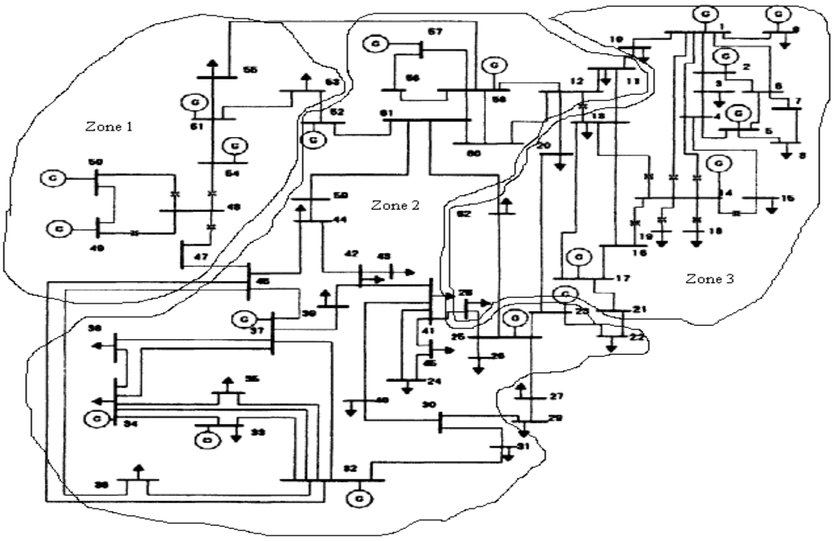


Fig.6 Congestion Zones for 62 Bus System

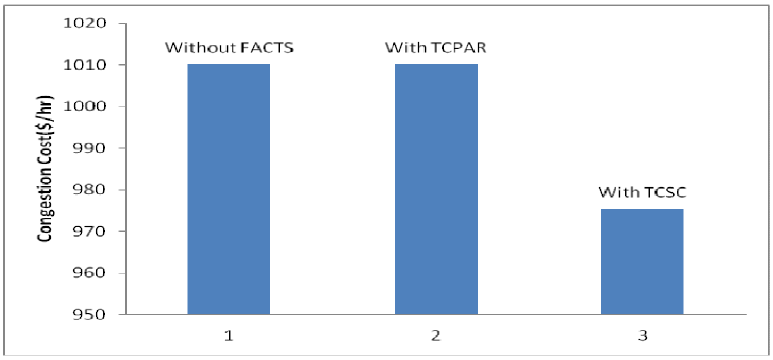


Fig.7 Congestion Cost for 62 Bus System without and with FACTS

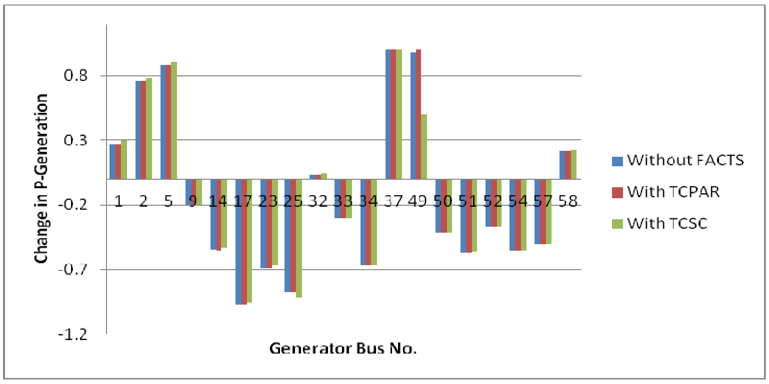


Fig.8 Change in P-Generation for 62 Bus System without and with FACTS

Table 1. TCDFs and Zones for 118 Bus System for congested line 8-5

Zone 1		**Zone 2**		**Zone 3**		**Zone 4**	
1,-0.5	21,-0.06	22,-0.043	115,-0.02	44,-0.005	65,0.001	83,0.0003	103, 0.0003
2,-0.5	27,-0.02	23,-0.01		45,-0.003	66,0.0007	84, 0.0003	104, 0.0004
3,-0.5	28,-0.03	24,-0.01		46,-0.001	67,0.0008	85, 0.0003	105, 0.0004
4,-0.6	29,-0.03	25,0.004		47,-0.001	68,0.001	86, 0.0003	106, 0.0004
5,-0.6	113,-0.06	26,0.01		48,-0.001	69,0.00	87, 0.0003	107, 0.0004
6,-0.5	117,-0.5	30,0.05		49,-0.0009	70,-0.003	88, 0.0003	108, 0.0004
7,-0.5		31,-0.04		50,-0.0007	71,-0.003	89, 0.0003	109, 0.0004
8,0.2		32,-0.03		51,-0.0004	72,-0.008	90, 0.0003	110, 0.0004
9,0.2		33,-0.07		52,-0.0004	73,-0.003	91, 0.0003	111, 0.0004
10,0.2		34,-0.01		53,-0.0002	74,-0.001	92, 0.0003	112, 0.0004
11,-0.5		35,-0.01		54,0.00	75,-0.001	93, 0.0003	
12,-0.5		36,-0.01		55,0.0001	76,-0.0007	94, 0.0003	
13,-0.4		37,-0.01		57,-0.0003	77,0.0001	95, 0.0003	
14,-0.4		38,0.01		58,-0.0002	78,0.0002	96, 0.0003	
15,-0.1		39,-0.01		59,0.0008	79,0.0002	97, 0.0003	
16,-0.3		40,-0.01		60,0.001	80,0.0004	98, 0.0003	
17,-0.06		41,-0.009		61,0.001	81,0.0008	99, 0.0003	
18,-0.08		42,-0.006		62,0.001	82,0.0002	100, 0.0003	
19,-0.09		43,-0.01		63,0.001	116,0.001	101, 0.0003	
20,-0.07		114,-0.02		64,0.001	118,0.001	102, 0.0003	

Table 2. Congestion cost for 118 bus system with and without FACTS

	Without FACTS	With TCSC	With TCPAR
Congestion Cost ($/hr)	7910.174	7890.168	7908.817

Table 3. TCDFs and Zones for 62 Bus System for congested line 48-47

Zone 1	**Zone 2**		**Zone 3**	
47,0.0004	11,0.0002	39, 0.0003	1,0.0001	19, 0.0001
48,0.0006	12, 0.0002	40, 0.0002	2, 0.0001	20, 0.0001
49,0.6	22,0.00	41, 0.0002	3, 0.0001	21, 0.0001
50,-0.11	23,0.00	42, 0.0002	4, 0.0001	27, 0.0001
51,0.0004	24, 0.0002	43, 0.0002	5, 0.0001	28, 0.0001
53,0.0004	25,0.00	44, 0.0002	6, 0.0001	29, 0.0001
54,0.0005	26,0.00	45, 0.0002	7, 0.0001	62, 0.0001
55,0.0003	30, 0.0002	46, 0.0003	8, 0.0001	
	31, 0.0002	52, 0.0003	9, 0.0001	
	32,0.0003	56, 0.0002	10, 0.0001	
	33, 0.0003	57, 0.0002	13, 0.0001	
	34, 0.0003	58, 0.0002	14, 0.0001	
	35, 0.0003	59, 0.0002	15, 0.0001	
	36, 0.0003	60, 0.0002	16, 0.0001	
	37, 0.0003	61, 0.0002	17, 0.0001	
	38, 0.0003		18, 0.0001	

Table 4. Congestion cost for 62 bus system with and without FACTS

	Without FACTS	With TCSC	With TCPAR
Congestion Cost ($/hr)	1010.198	975.4203	1010.087

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