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Zonal Power Quality improvement using Static Var Compensator for an Indian Utility System

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ABSTRACT

Power quality is an issue that is becoming increasingly important to electricity consumers at all levels of usage.

In this paper, a new power quality index is proposed for power quality improvement considering zones using FACTS devices. In this paper, transmission congestion distribution factors based on sensitivity of line real power has been proposed to identify the congestion clusters. This presents an optimal allocation method for Static Var Compensator based on sensitivity method. The effectiveness of the proposed method is tested and verified on 124 bus Indian Utility System.

Keywords – **Congestion Zones, Power Quality, Static Var Compensator, Sensitivity,**

I. INTRODUCTION

Power quality in electric networks is one of today's most concerned areas of electric power system. The power quality has serious economic implications for consumers, utilities and electrical equipment manufacturers. Modernization and automation of industry involves increasing use of computers, microprocessors and power electronic systems such as adjustable speed drives. Under deregulated environment, in which electric utilities are expected to compete with each other, the customer becomes very important [1]. The impact of power quality problems is increasingly felt by customers- industrial, commercial and even residential.

Recent developments in electrical power systems such as deregulation, open access, and cogeneration are creating scenarios of transmission congestion and forced outages. Addition of new transmission lines is an almost impossible solution due to environmental and other considerations, and developing new approaches to Power System Operation and Control is the need of the hour for overload relief and efficient and reliable operation. Flexible AC Transmission Systems (FACTS), with the underlying concept of independent control of active and reactive power flows, offer an attractive alternative for achieving the objectives.

The use of static power converters in electricity networks has the potential of increasing the capacity of transmission of the electric lines and improving the supply quality of the electric energy.

II. MATHEMATICAL FORMULATION

Static Var Compensator

Static VAR Compensator (SVC) is a shunt connected FACTS controller whose main functionality is to regulate the voltage at a given bus by controlling its equivalent reactance [2]. The Shunt Compensator SVC is simply considered as a static capacitor/reactor with susceptance B_{svc}. Fig.1 shows the equivalent circuit of the SVC can be modeled as a shunt connected variable susceptance B_{svc} at bus-*i*.

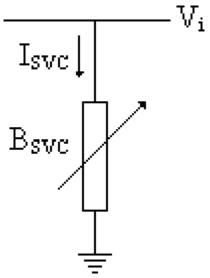

Fig.1 Variable shunt susceptance

The reactive power injected into the bus due to SVC can be expressed as

$$Q_{SVC} = B_{SVC} V_i^2 \qquad (1)$$

Where V is the voltage magnitude of the bus at which the SVC is connected. Fig. 2 shows the steady-state and dynamic voltage-current characteristics of the SVC portion of the system [3]. At the capacitive limit, the SVC becomes a shunt capacitor. At the inductive limit, the SVC becomes a shunt reactor (the current or reactive power may also be limited). The response shown by the dynamic characteristic is very fast (few cycles) and is the response normally represented in transient stability simulation. Some SVCs have a current/reactive power regulator to slowly return the SVC to a desired steady state operating point. This prevents the SVC from drifting towards its limits during normal operating conditions, preserving control margin for fast reaction during disturbances [4]. During normal operation, voltage is not regulated unless the voltage exceeds a dead band determined by the limits on the output of the susceptance regulator.

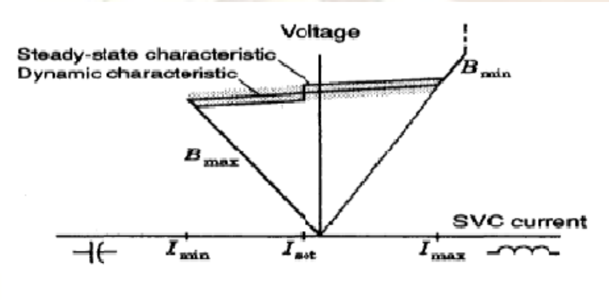

Fig. 2: SVC static characteristics at high voltage bus.

After adding SVC at bus-i of a general power system, the new system admittance matrix $Y_{bus}^{'}$ can be updated as:

$$Y_{bus}^{'} = Y_{bus} + \begin{bmatrix} O & O.... & O & O \\ O & O.... & O & O \\ . & ...... & . & . \\ . & ..... & . & . \\ O & O.... & O & O \\ O & O.... & O & O \end{bmatrix} \qquad (2)$$

Transmission congestion distribution factors

Transmission congestion distribution factors [5] are defined as the change in real power flow 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:

$$TCDF_i^k = \frac{\Delta P_{ij}}{\Delta P_i} \qquad (3)$$

where P_{ij} 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_{ij}) in a line-*k* connected between bus-*i* and bus-*j* can be written as:

$$P_{ij} = V_i V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) - V_i^2 Y_{ij} \cos\theta_{ij} \qquad (4)$$

Using Taylor's series approximation and ignoring higher order terms, Eq. (4) can be written as:

$$\Delta P_{ij} = \frac{\partial P_{ij}}{\partial \delta_i}\Delta\delta_i + \frac{\partial P_{ij}}{\partial \delta_j}\Delta\delta_j + \frac{\partial P_{ij}}{\partial V_i}\Delta V_i + \frac{\partial P_{ij}}{\partial V_j}\Delta V_j \qquad (5)$$

Eq. (5) can be rewritten as:

$$\Delta P_{ij} = a_{ij}\Delta\delta_i + b_{ij}\Delta\delta_j + c_{ij}\Delta V_i + d_{ij}\Delta V_j \qquad (6)$$

The coefficients appearing in Eq. (6) can be obtained using the partial derivatives of real power flow Eq. (4) with respect to variables δ and V as:

$$a_{ij} = V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) \qquad (7)$$

$$b_{ij} = -V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) \qquad (8)$$

$$c_{ij} = V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) - 2V_i Y_{ij} \cos\theta_{ij} \qquad (9)$$

$$d_{ij} = V_i Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) \qquad (10)$$

For determination of TCDFs [6] the following Jacobian relationship has been used

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

Neglecting coupling between ΔP and ΔV and between ΔQ and $\Delta\delta$, Eq. (11) can be simplified as:

$$\Delta P = [J_{11}][\Delta\delta] \qquad (12)$$

$$\Delta Q = [J_{22}][\Delta V] \qquad (13)$$

From Eq. (12), we get:

$$\Delta\delta = [J_{11}]^{-1}[\Delta P] = [M][\Delta P] \qquad (14)$$

Eq. (14) can be written in the form:

$$\Delta\delta_i = \sum_{l=1}^{n} m_{il}\Delta P_l \qquad i = 1,2,....n, i \neq s \qquad (15)$$

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. (15) can be written as:

$$\Delta P_{ij} = a_{ij}\Delta\delta_i + b_{ij}\Delta\delta_j \qquad (16)$$

Substituting Eq. (15) into Eq. (16), we get:

$$\Delta P_{ij} = a_{ij}\sum_{l=1}^{n} m_{il}\Delta P_l + b_{ij}\sum_{l=1}^{n} m_{jl}\Delta P_l \qquad (17)$$

$$\begin{aligned}\Delta P_{ij} &= (a_{ij}m_{i1} + b_{ij}m_{j1})\Delta P_1 + \\ &(a_{ij}m_{i2} + b_{ij}m_{j2})\Delta P_2 + ...+ (a_{ij}m_{in} + b_{ij}m_{jn})\Delta P_n\end{aligned} \qquad (18)$$

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

$$\Delta P_{ij} = TCDF_1^k \Delta P_1 + TCDF_2^k \Delta P_2 + ...+ TCDF_n^k \Delta P_n \qquad (19)$$

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* [7].

III. OPTIMAL LOCATION OF STATIC VAR COMPENSATOR

For computing the loss sensitivity index with respect to SVC an exact loss formula has been used [8] , which expresses Q_L as,

$$Q_L = \sum_{i=1}^{NB}\sum_{j=1}^{NB}\left[c_{ij}(P_iP_j + Q_iQ_j) + d_{ij}(Q_iP_j - P_iQ_j)\right] \qquad (20)$$

where c_{ij} and d_{ij} are the loss coefficients defined as,

$$c_{ij} = \frac{X_{ij}}{|V_i||V_j|}\cos(\delta_i - \delta_j)$$

$$d_{ij} = \frac{X_{ij}}{|V_i||V_j|}\sin(\delta_i - \delta_j)$$

P_i+jQ_i is the complex injected power at bus *i* and X_{ij} is the imaginary part of the *ij*th element of [*Z*bus].

At bus *i*, the sensitivity index (C_i) with respect to the SVC parameter using the above loss formula can be expressed as,

$$C_i = \frac{\partial Q_L}{\partial Q_i} = 2\sum_{j=1}^{NB}(Q_j c_{ij} + P_j d_{ij}) \qquad i=1 \ldots NB \qquad (21)$$

The SVC should be placed at a bus *i* having most negative sensitivity index *Ci*. The placement of SVC has been considered at load buses only.

IV. CONGESTION ZONE BASED POWER QUALITY IMPROVEMENT

The TCDFs obtained based on the methodology discussed have been utilized 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 [9]. 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.

In this paper, based on the TCDFs, the SVC is placed optimally in each zone at load buses.

Power Quality Index

A new power quality index is proposed to improve the power by optimally placing SVC

$$PQ_{idx} = \frac{\sum_{i=1}^{n}(|V| - |V_i|)^2}{n} \qquad (22)$$

Where $|V|$ is the voltage at which SVC is placed

$|V_i|$ is the voltage of bus i in a zone.

n is the number of buses in a zone.

V. RESULTS AND DISCUSSIONS

The Proposed concept of Zonal power quality improvement utilizing the TCDFs is illustrated on a 124 bus Indian Utility System.

124 bus Indian Utility system

For this system the congestion clusters/zones based on the proposed method for a line of interest 46-20 are shown in Fig3.

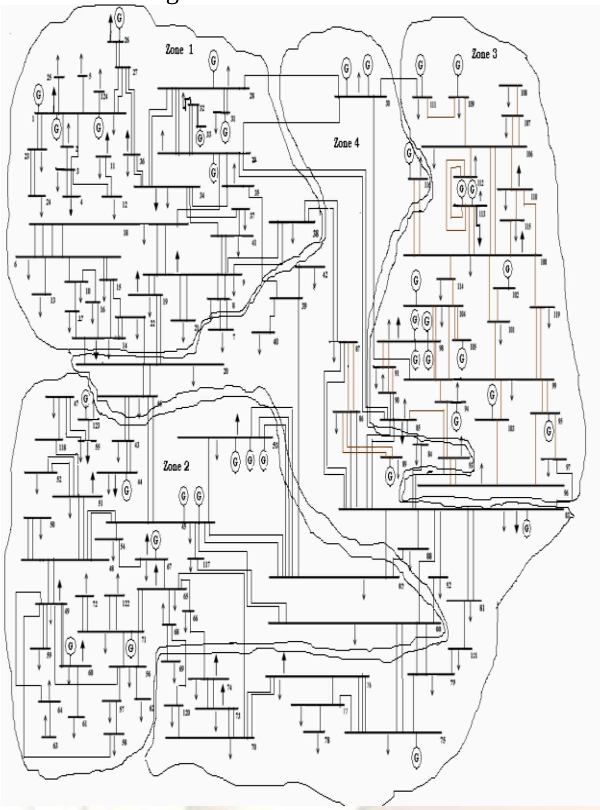

Fig.3 Congestion Zones for 124 Bus System

The TCDFs for the congested line 46-20 corresponding to each bus are given in Table I for the four different zones. The zone 4 is the most sensitive zone with larger magnitude and strongest non-uniform distribution of TCDFs. The magnitudes of TCDFs in zone 2 are higher than zone 1,3 but due to uniform distribution of TCDFs, the zone 2 is least sensitive zone.

The Sensitivity indices for SVC are calculated, by observing the sensitivity indices, bus 9 has most negative sensitivity index in zone 1. Therefore, bus 9 is chosen as the optimal location for placing SVC which is having the most negative sensitivity index in zone1. SVC is placed at bus 9 in zone 1. Similarly, bus 68 has most negative sensitivity index in zone 2. Therefore, SVC is placed at bus 68 in zone 2. Similarly, bus 101 has most negative sensitivity index in zone 3. Therefore, SVC is placed at bus 101 in zone 3. Similarly, bus 76 has most negative sensitivity index in zone 4. Therefore, SVC is placed at bus 76 in zone 4.

Table 1. TCDFs and Zones for 124 bus system for congested line 46-20

Zone 1		**Zone 2**		**Zone 3**	**Zone 4**	
Bus, TCD	Bus, TCDF	Bus, TCDF	Bus, TCDF	Bus, TCDF	Bus, TCDF	Bus, TCDF
1, -0.09	26, -0.09	45,0.1	71, 0.1	85,-0.005	7,-0.2	89,-0.004
2, -0.09	27, -0.09	47, 0.1	72, 0.1	90, -0.01	20,-0.3	91,-0.01
3, -0.09	28, -0.09	48, 0.1	78, 0.1	94, -0.02	30,0.06	92,0.09
4, -0.09	29, -0.09	49, 0.1	80, 0.1	95, -0.02	35,-0.01	93-0.01,
5, -0.1	31, -0.09	50, 0.1	82, 0.1	98, -0.02	39,0.06	96,-0.02
6, -0.3	32, -0.09	51, 0.1	88, 0.1	99, -0.02	40,0.06	97,-0.01
8, -0.2	33, -0.09	52, 0.1	117, 0.1	100, -0.03	42,0.06	116,-0.01
9, -0.2	34, -0.1	53, 0.1	118, 0.1	101, -0.02	43,0.4	120,0..03
10, -0.3	36, -0.09	54, 0.1	122, 0.1	102, -0.02	44,0.4	121,0.08
11, -0.09	37, -0.1	55, 0.1	123, 0.1	103, -0.02	46,0.4	
12, -0.09	38, -0.1	56, 0.1		104, -0.02	69,0.1	
13, -0.3	41, -0.2	57, 0.1		105, -0.02	70,0.1	
14, -0.3	124, -0.1	58, 0.1		106, -0.03	73,0.1	
15, -0.3		59, 0.1		107, -0.03	74,0.1	
16, -0.3		60, 0.1		108, -0.04	75,0.1	
17, -0.3		61, 0.1		109, -0.05	76,0.1	
18, -0.3		62, 0.1		110, -0.03	77,0.1	
19, -0.3		63, 0.1		111, -0.05	79,0.09	
21, -0.2		64, 0.1		112, -0.03	81,0.09	
22, -0.3		65, 0.1		113, -0.03	83,0.0	
23, -0.1		66, 0.1		114, -0.03	84,-0.004	
24, -0.1		67, 0.1		115, -0.03	86,-0.004	
25, -0.1		68, 0.1		119, -0.02	87,-0.04	

Nominal Mvar of SVC is varied from 10 Mvar to 50 Mvar and PQ_{idx} is calculated for each zone and are tabulated in Table II. The graphs corresponding to variation of nominal Mvar of SVC to the power quality index for each zone is shown in fig. 4.

Table 2 (a). Power quality index at zone 1 with SVC at bus 9

Mvar	PQ_{idx}
10	0.00344
20	0.003627
30	0.003826
40	0.004038
50	0.004261

Table 2 (b). Power quality index at zone 2 with SVC at bus 68

Mvar	X
10	0.000313
20	0.000257
30	0.000239
40	0.00026
50	0.00032

Table 2 (c). Power quality index at zone 3 with SVC at bus 101

Mvar	X
10	0.00013
20	0.000132
30	0.000135
40	0.000137
50	0.00014

Table 2 (d). Power quality index at zone 4 with SVC at bus 76

Mvar	X
10	0.001512
20	0.001635
30	0.001765
40	0.001901
50	0.002043

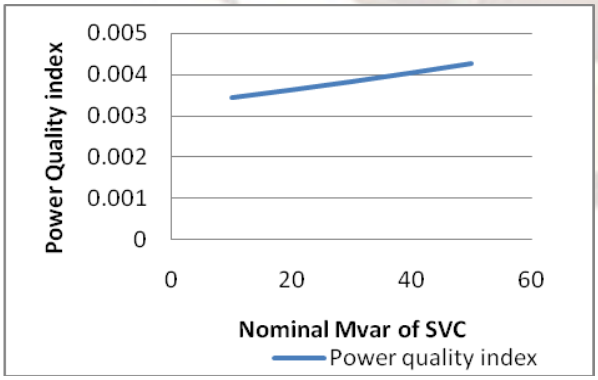

Fig. 4(a) Variation of power quality index with SVC st bus 9 in zone 1

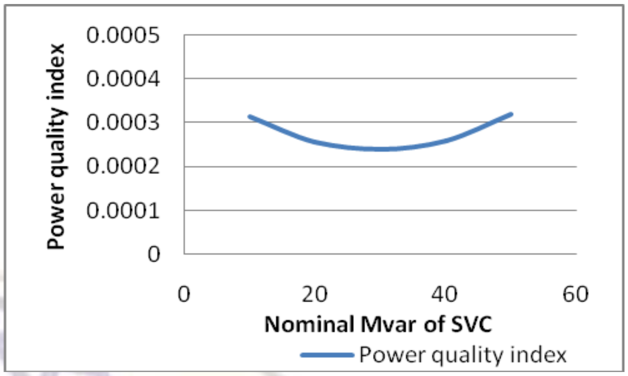

Fig. 4(b) Variation of power quality index with SVC at bus 68 in zone 2

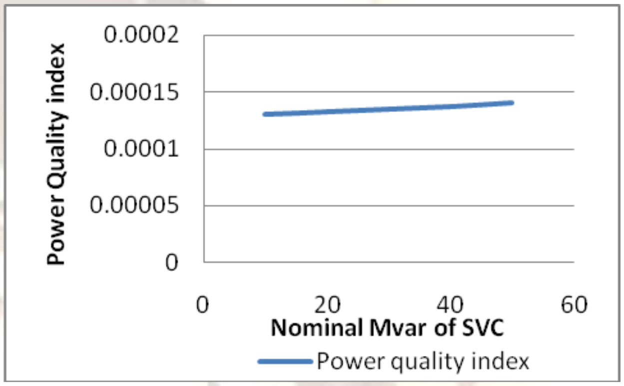

Fig. 4(c) Variation of power quality index with SVC at bus 101 in zone 3

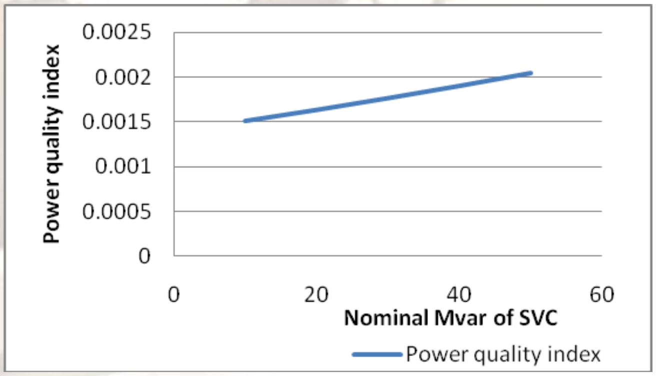

Fig. 4(d) Variation of power quality index with SVC at bus 76 in zone 4

By observing the graphs between power quality index and the nominal Mvar of SVC at bus 9, 68,101and 76 in zones 1,2,3,4 respectively, power quality has been improved by proposed index with optimal placement of SVC by increasing the nominal Mvar.

VI. CONCLUSIONS

This paper proposes a new index for power quality improvement based on congestion zones/clusters obtained with new set of transmission congestion distribution factors. The optimal location of SVC has been determined based on sensitivity index. In this paper optimal location of SVC is placed in each zone. It is observed that the power quality has been improved by placing SVC optimally in each zone by the proposed index.

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