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Effects of Tap Changing Transformer and Shunt Capacitor on Voltage Stability Enhancement of Transmission Networks

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Abstract**—**Voltage stability has become an important issue to many power systems around the world due to the weak systems and long line on power system networks. In this paper, MATLAB load flow program is applied to obtain the weak points in the system combined with finding the voltage stability limit. The maximum permissible loading of a system, within the voltage stability limit, is usually determined. The methods for varying tap ratio (using tap changing transformer) and applying different values of shunt capacitor injection to improve the voltage stability within the limit are also provided.

Keywords**—**Load flow, Voltage stability, Tap changing transformer, Shunt capacitor injection, Voltage stability limit

I. INTRODUCTION

THE basic function of voltage regulation in the transmission system operation is to keep the steady state voltage in the system stable within an acceptable range all the time. The desired voltages can be obtained by either directly controlling the voltage or by controlling the reactive power flow that in turn will affect the voltage drop [6]. The equipments normally used for voltage stability and reactive power control are tap changing transformers and shunt capacitor injection [8]. In general, voltage magnitude of a substation is controlled by tap changing transformer and several capacitor banks; the transformer changes its tap position to control the lower side voltage magnitude directly, whereas the capacitor banks affect the higher side voltage magnitude indirectly by changing the amount of reactive power demand at the bus [2]. This paper introduces using tap changing transformer and shunt capacitor injection and its main feature. Section II describes a method as an accurate algorithm to analyze voltage stability for power system with an individual bus. Description of system weak point by Newton-Raphson load flow method and determination of voltage stability limit are discussed in section III. Finally, a conclusion is made based on the results of voltage stability analysis.

II. VOLTAGE STABILITY

When a state of voltage instability occurs, there is a progressive or uncontrollable drop in voltage magnitude after a disturbance, increase in load demand or change in operating condition. The main factor causing voltage instability is the inability of the power system to maintain a proper balance of reactive power throughout the system and, therefore, it is often associated with systems in adequate poorly located generating sources and insufficient transmission facilities [5]. Under normal operating conditions, the bus voltage magnitude (V) increases as reactive power (Q) injected at the same bus is increased. When the bus voltage magnitude (V) of any one of the system's buses decreases with the increase in reactive power (Q) for that same bus, the system is said to be unstable Although the voltage instability is a localized problem, its impact on the system can be wide spread as it depends on the relationship between transmitted P, injected Q and receiving end V. These relationships play an important role in the stability analysis and can be displayed graphically [7].

III. DESCRIPTION OF SYSTEM WEAK POINT BY NEWTON-RAPHSON LOAD FLOW METHOD

In the Newton-Raphson load flow method, the voltage magnitude is set to 1.0 per unit and the specified voltage variation limit is ±5%. So the voltage magnitude (limits of the safe voltage) in system buses must be in the range of 1.05 per unit to 0.95 per unit. The weak points in the system have the voltage magnitude under 0.95 [4].

A. Newton-Raphson Load Flow Method

The maximum permissible loading of a system, within the voltage stability limit, is usually determined from the well known PV curve or QV curve. The Newton-Raphson load flow method is applied to solve the complex power flow equation.

$$P_i = \sum_{k=1}^{N} \left| V_i V_k Y_{ik} \right| \cos\left(\phi_{ik} + \delta_k - \delta_i\right) i = 1,2,3,...,(N-1) \quad (1)$$

$$Q_i = -\sum_{k=1}^{N} \left| V_i V_k Y_{ik} \right| \sin\left(\phi_{ik} + \delta_k - \delta_i\right) i = 1,2,3,...,(N-1) \quad (2)$$

Where V (voltage), P (real power) and Q (reactive power) terms are given in per unit and δ (phase angle) terms are in radians. Equation (1) and (2) show that the real and reactive powers at every bus expect the slack bus can be expressed as a function of voltage magnitude and phase angles [4].

B. Analytical Concept of Voltage Stability

The first step in QV curve method of voltage stability analysis is to solve the complex power flow equation of an uncompensated basis transmission system model [1]. Equation (3) and (4) give real and reactive power expressions of a loss –less power transmission system at load buses.

$$P = -\frac{EV}{X}\sin\theta \quad (3)$$

$$Q = -\frac{V^2}{X} + \frac{EV}{X}\cos\theta \quad (4)$$

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$$V=\left[\frac{-2QX+E^{2}}{2}\pm\frac{1}{2}\sqrt{(2QX-E^{2})^{2}-4X^{2}(P^{2}+Q^{2})}\right]^{\frac{1}{2}} \qquad (5)$$

C. *Test System Networks*

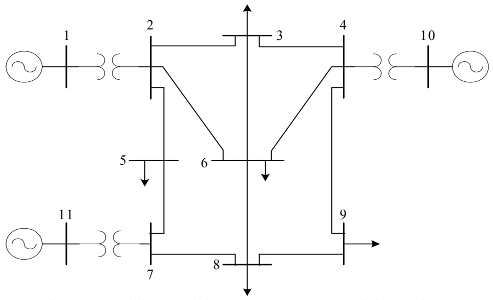

Fig. 1 Multi-machine test system with 11 buses

The simplified diagram of test system which consists of 11 busbars, 14 transmission lines, 3 machines is shown in Fig. 1.

D. *Base Case Condition*

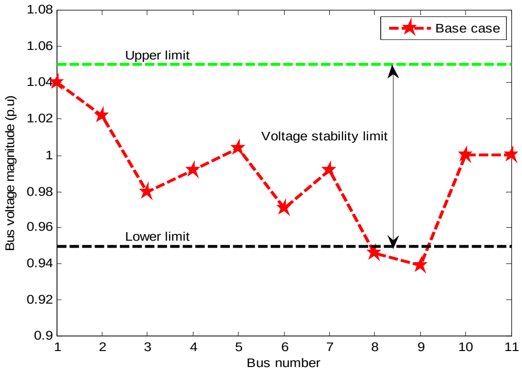

Fig.2 Base case condition

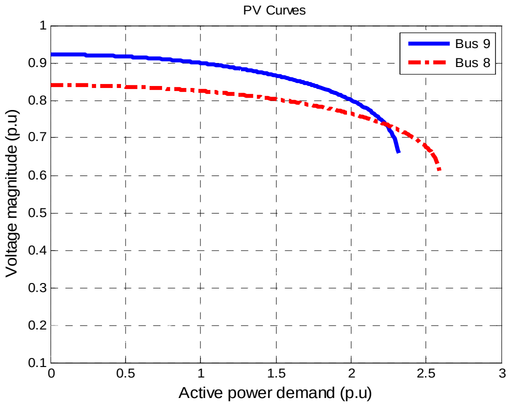

Fig.3 PV curves for 11-bus test system

In normal condition, voltage in per unit (p.u) at all buses in transmission system network does not in acceptable range (voltage stability limit). The result in term of voltage at all 11 buses in base case condition is shown in Fig. 2. PV and QV curves are essential for finding the maximum or critical loading point (CLP) in power system. Active power demand (MW) distance from operating point to critical voltage and maximum power transfer limit at the weak buses are shown in Fig 3. Reactive power demand (MVAR) distance to voltage stability margin and maximum reactive capability at the weak buses are presented in Fig 4. The results summary for weak points at 11 buses systems is described in Table 1.

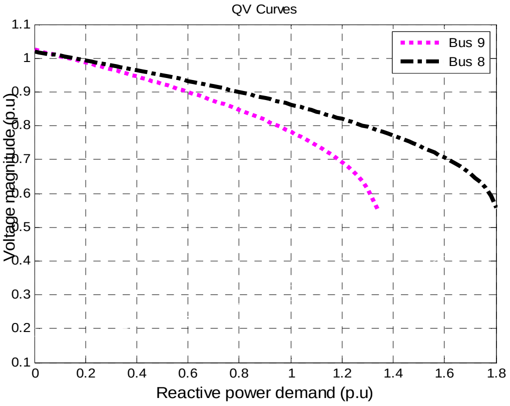

Fig.4 QV curves for 11-bus test system

TABLE I
RESULTS SUMMARY FOR WEAK POINTS IN TEST SYSTEM

Bus No	Voltage Magnitude (p.u)	PV Curve		QV Curve	
		Critical Voltage (p.u)	Collapse MW (p.u)	Critical Voltage (p.u)	Collapse MVAR (p.u)
8	0.946	0.6251	2.59	0.5564	1.8
9	0.940	0.6580	2.32	0.5481	1.34

E. *The Effects of Tap Changing Transformer*

TABLE II
RESULTS OF 11 BUSES SYSTEM AFTER VARYING TAP RATIO

Bus Numbers	Voltage Magnitude (p.u)			
	Base Case	Tap Ratio (T)		
		T1 =0.95	T2 = 0.975	T3 = 1.025
1	1.04	1.04	1.04	1.04
2	1.022	1.013	1.017	1.027
3	0.98	0.953	0.967	0.992
4	0.992	0.948	0.971	1.014
5	1.004	0.986	0.995	1.013
6	0.971	0.942	0.957	0.986
7	0.992	0.949	0.971	1.013
8	0.946	0.906	0.926	0.966
9	0.940	0.896	0.918	0.960
10	1.000	1.000	1.000	1.000
11	1.000	1.000	1.000	1.000

In order to improve the voltage stability, tap changing transformer is known that have ability to control the voltage in transmission system within the limit. This method also identifies critical load tap changing transformers to be made manual under peak load conditions to prevent possible voltage instability. The best tap ratio that produce output result within voltage stability limit at all 11 buses was selected at corresponding transformer [9].

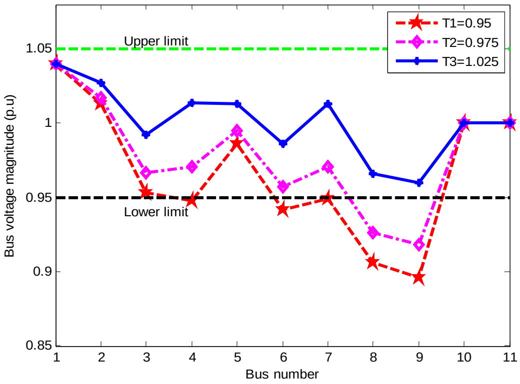

Fig.5 Tap ratio variation in test system

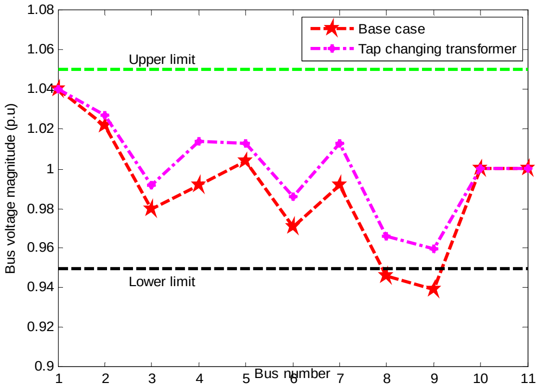

Fig.6 Comparison of bus voltage magnitude (Tap Changing Transformer)

Variation of tap changer of transformer is doing by adjust tap ratio with step size 0.025 from minimum tap ratio until maximum tap ratio. The voltage variation as varying the tap ratio at corresponding transformer is indicated in Fig 5. Comparison of bus voltage magnitude describes as shown in Fig. 6. The results of 11 buses system after varying tap ratio are described in Table 2.

F. The Effects of Injection of Shunt Capacitor

TABLE III
RESULTS OF 11 BUSES SYSTEM AFTER APPLYING SHUNT CAPACITOR

Bus Numbers	Voltage Magnitude (p.u)			
	Base Case	Qc = 6 MVAR	Qc = 15 MVAR	Qc = 25 MVAR
1	1.04	1.04	1.04	1.04
2	1.022	1.022	1.022	1.022
3	0.98	0.98	0.98	0.981
4	0.992	0.993	0.993	0.994
5	1.004	1.005	1.005	1.005
6	0.971	0.972	0.972	0.973
7	0.992	0.992	0.993	0.993
8	0.946	0.947	0.949	0.95
9	0.940	0.942	0.946	0.95
10	1.000	1.000	1.000	1.000
11	1.000	1.000	1.000	1.000

Shunt capacitors are employed at transmission level for voltage regulation, reducing power losses and increased utilization of equipment. The main reason that shunt capacitors are installed at bus bars is to control the voltage within required levels [3].

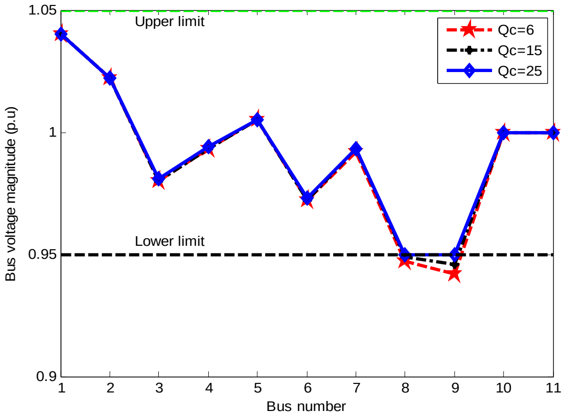

Fig.7 Different value of reactive compensation

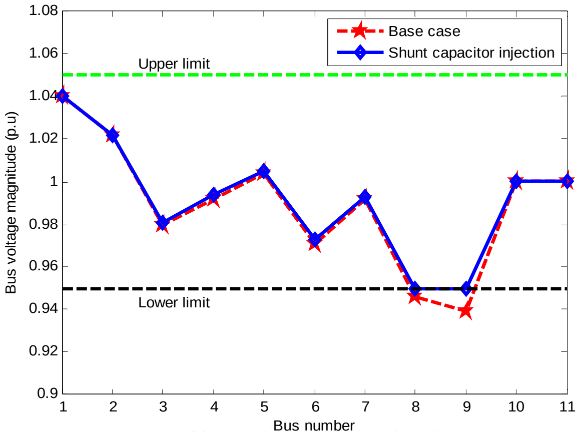

Fig.8 Comparison of bus voltage magnitude (Shunt Capacitor Injection)

But this paper use the shunt capacitor injection because it has no moving parts, initial cost is low, reaction in failures. The results of 11 buses system after applying shunt capacitor are indicated in Table 3. Shunt capacitor banks can be permanently connected to the bus (fixed capacitor bank) or can be switched as needed. Shunt capacitor injections were varied to get the variation in voltages at all buses as shown in Fig 7. The value of reactive compensation that produces voltage within the limit was selected at the weakest bus. Mechanically switched shunt capacitors will be able to mitigate voltage in stability with a time frame longer than minute. However, the mechanically switched shunt capacitors are too slow to mitigate transient voltage in stability with a time frame from a few hundreds of milliseconds. In Fig. 8, the voltage at bus 9 and 8 after shunt capacitor injection became 0.95 (p.u) at each bus.

G. Comparison between Tap Changing Transformer and Shunts Capacitor Injection

The results of voltage stability and total power losses are shown in Table 4. It will concern the minimum, maximum and average voltage which is to describe the voltage whether within stability or not. It can be seen in Fig. 9 that the comparison between methods of voltage control that cause the voltage variation at all buses in transmission system network. In base case condition, the graph shows that not all buses within voltage stability limit which is 0.95 < V < 1.05 p.u. After implementing the methods of voltage control that is tap changing transformer and shunt capacitor injection, it can be seen the improvement in term of voltage at all buses within stability limit. So, the methods were suitable in order to improve voltage stability in transmission network. The graph also shows which methods react better towards voltage control in stability limit.

TABLE IV
RESULTS OF VOLTAGE STABILITY AND TOTAL POWER LOSSES

	Minimum Voltage (p.u)	Maximum Voltage (p.u)	Average Voltage (p.u)	Total Power losses (MW)
Base Case	0.940	1.04	0.9895	9.535
Tap Changing Transformer	0.960	1.04	1.000	8.532
Shunt Capacitor Injection	0.950	1.04	0.997	9.013

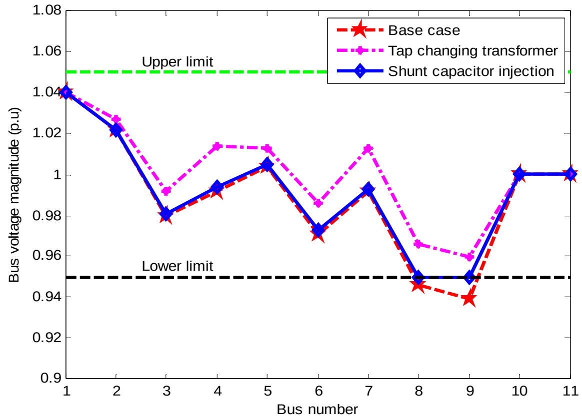

Fig.9 Comparison between methods of voltage control

In base case condition, the graph shows that not all buses within voltage stability limit which is $0.95 < V < 1.05$ p.u. After implementing the methods of voltage control that is tap changing transformer and shunt capacitor injection, it can be seen the improvement in term of voltage at all buses within stability limit. So, the methods were suitable in order to improve voltage stability in transmission network. The graph also shows which methods react better towards voltage control in stability limit. Therefore tap changing transformer is the better method compared to shunt capacitor method towards voltage stability improvement and reducing total power losses.

IV. CONCLUSION

In this paper, the insertion of tap changing transformers, and shunt capacitor injections are applied to improve voltage stability of the transmission networks. When the shunt capacitors under optimum value were installed at the weakest bus, the voltage of that bus was increased within the acceptable range. But the voltage improvement cannot be affected in all buses very much. According to the simulation results, the effects of all bus voltages changed and improved within the stability limit because of varying of the best condition of tap ratio. Therefore, applying tap changing transformers was more reasonable than injection of shunt capacitor in order to improve the voltage stability and reduce total power losses.

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