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Monitoring the effects of On-Load Tap Changing Transformers on Voltage stability

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Abstract**-- It is becoming increasingly important for power system planning and operating engineers to be capable of performing comprehensive voltage stability analyses of the systems. This need is largely due to recent trends towards operating systems under stressed conditions as a result of increasing system loads without sufficient transmission and/or generation enhancements. This paper discusses effect of the On-load tap changing transformers (OLTCs) on voltage stability and identifying critical OLTCs to avoid possibilities of voltage instability conditions. The developed approach has been tested on sample systems. Results obtained on an equivalent system of 24-node practical power system are presented.**

Index Terms**-- Voltage stability, OLTC transformers.**

I. INTRODUCTION

THE voltage stability problem has become a major concern in operating and planning today's power system as a result of heavier loading conditions, without sufficient transmission and/or generation enhancements. Voltage stability problems normally occur in heavily stressed systems. While the disturbance leading to Voltage collapse may be initiated by a variety of causes, the underlying problem is an inherent weakness in the power system. The factors contributing to Voltage collapse are the generator reactive power /Voltage control limits, load characteristics, characteristics of reactive compensation devices, and the action of the voltage control devices such as transformer on – load tap changers (OLTCs). Power system experiencing an abnormal operating conditions following a disturbance, the EHV level voltage reduction at load centers would be reflected into the distribution system. The OLTCs of distribution transformers would restore distribution voltages, with each tap change operation, the resulting increment in load on EHV lines would increase the MWs, MVARs, losses, which intern would cause a great drops in EHV levels. As a result, with each tap - changing operation, the reactive output of generators throughout the system would increase gradually, the generators would hit their reactive power capability limits. The process will eventually may lead to voltage collapse. Thus the operation of on-load tap changers (OLTCs) has a significance influence on voltage instability. Zhu et al. [1] addresses the effects of OLTC operation on voltage collapse from the point of view of how the limit of power transfer from the generation to the load center can be affected by OLTC operation. Isaias et al. [2] shown that blocking the tap changes in the OLTCs may prevent voltage collapse, while maximizing the load recovered. For this sake, the blocking time is determined by a tangent vector – based index. The index proposed is based on voltage level variation at the bus controlled as a function of tap changes. Costas Vournas et al. [3] presents emergency control of bulk power delivery load tap changers focusing on tap reversing, when transmission voltage becomes low. In this an algorithm is suggested for the determination of optimal LTC settings that maximize the loadability margin for a specific active power pattern. Mamandur et al. [4] addresses the effect of the control variables (transformer taps) on the system losses. Thukaram et al. [5] is mainly concerned with analysis and enhancement of steady state voltage stability based on L-index an algorithm is proposed for optimization of reactive power control variables using Linear-programming technique. This paper presents an approach for monitoring the on – load tap changing transformers effect on voltage stability and identifying the critical transformers which may lead to voltage instability under peak load conditions. The approach is based on voltage stability L-index. The proposed approach is tested on few sample systems and results obtained on a 24-node EHV 400kV Indian power system network.

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II. APPROACH

Network security analysis and optimization form the core functions in a modern energy control center (ECC). The system status is obtained from the output of an on-line state estimator. The output of the state estimator is checked for limit violations and if the system is insecure then corrective control action has to be taken. If the system is operating in a secure state, then the system is subjected to a subset of credible contingencies and the system status is evaluated. If after a contingency study the system status indicates insecure operation, then suitable preventive control action is formulated. If voltage violations are present, then an optimal reactive power dispatch is obtained. The objectives generally used are:

- Minimization of real power losses (P_{loss}) in the system or
- Minimization of voltage deviations from desired voltage values ($V_{desired}$).

Both the objectives achieve their desired minimum by optimal control of the reactive power control variables .The controls recommended while achieving this objective may in certain cases actually deteriorate the system voltage stability condition under stressed conditions, especially when using OLTC transformers. While OLTC transformers improve the voltage profile at the load end (especially with objective Vdesired) by change of the tap position (boost to low voltage side), this may lead to voltage instability conditions due to inadequate reactive power support. Hence, from the system security point of view, an objective function, which incorporates improvement of the voltage stability margin, is found to be necessary. Since the L–index value indicates the proximity of the system to voltage collapse; we have selected minimization of the sum square of L – indices as the objective ($V_{stability}$). This objective recommends optimal control of the reactive power control variables such that the overall system stability is improved.

In case of objective $V_{desired}$ or P_{loss} the controller action, especially the direction of tap change recommended may be opposite to the tap change direction recommended by the proposed objective. This is because objective Vdesired or Ploss tries to improve the secondary side voltage by recommending tap variation towards the 0.9 setting , but under heavy load conditions this may actually deteriorate the system voltage stability margin. Therefore, the proposed objective also helps in identifying critical OLTCs, which should be made manual to avoid possibilities of voltage instability conditions due to the operation of OLTC transformers based exclusively on voltage stability criteria.

III. Voltage stability analysis using L- index

Consider a system where, n=total number of busses, with 1, 2... g generator busses (g), g+1, g+2... g+s SVC busses (s), g+s+1... n the remaining busses (r=n-g-s) and t =number of OLTC transformers.

A load flow result is obtained for a given system operating condition, which is otherwise available from the output of an on-line state estimator. Using the load flow results, the L-index [6] is computed as

$$L_j = \left| 1 - \sum_{i=1}^{g} F_{ji} \frac{V_i}{V_j} \right| \qquad (1)$$

where j=g+1... n and all the terms within the sigma on the RHS of (1) are complex quantities. The values F_{ji} are obtained from the Y bus matrix as follows

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \qquad (2)$$

where $I^G, I^L,$ and V^G, V^L represent currents and voltages at the generator nodes and load nodes. Rearranging (2) we get

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \qquad (3)$$

where $F^{LG} = -\left[Y^{LL}\right]^{-1}\left[Y^{LG}\right]$ are the required values. The L-indices for a given load condition are computed for all load busses.

For stability, the bound on the index L_j must not be violated (maximum limit=1) for any of the nodes j. Hence, the global indicator L describing the stability of the complete subsystem is given by L=maximum of L_j for all j (load buses). An L-index value away from 1 and close to zero indicates an improved system security. For a given network, as the load/generation increases, the voltage magnitude and angles change, and for near maximum power transfer condition, the voltage stability index L_j values for load buses tend to close to 1, indicating that the system is close to voltage collapse. The stability margin is obtained as the distance of L from a unit value i.e. (1-L).

IV. Description of the reactive power optimization problem

The model selected for the reactive power optimization uses linearized sensitivity relationships to define the optimization problem. The objective is to minimize the voltage stability objective function $v_L = \sum L^2$ in the system. The constraints are the linearized network performance equations relating the control and dependent variables and the limits on the control and dependent variables. The control variables are:

- The transformer tap settings (T),
- The generator excitation settings (V),
- The switchable VAR compensator (SVC) settings (Q).

These variables have their upper and lower limits. Changes in these variables affect the distribution of the reactive power and therefore change the reactive power at generators, the voltage profile and thus the voltage stability of the system. The dependent variables are:

- The reactive power outputs of the generators (Q),
- The voltage magnitude of the buses other than the generator buses (V).

These variables also have their upper and lower limits. In mathematical form, the problem is expressed as:

Minimize,

$$v_L = cx \qquad (4)$$

Subject to,

$$b^{\min} \le b = sx \le b^{\max} \qquad (5)$$

and

$$x^{\min} \le x \le x^{\max} \qquad (6)$$

Where C is the row matrix of the linearized loss sensitivity coefficients, S the linearized sensitivity matrix relating the dependent and control variables, b the column matrix of linearized dependent variables, x the column matrix of the linearized control variables, $b^{\max}$ and $b^{\min}$ are the column matrices of the linearized upper and lower limits on the dependent variables and x^{max} and x^{min} are the column matrices of linearized upper and lower limits on the control variables.

The linear programming technique is now applied to the above problems to determine the optimal settings of the control variables.

The control vector in incremental variables is defined as

$$x=\left[\Delta T_1,\ldots,\Delta T_t,\Delta V_1,\ldots,\Delta V_g,\Delta T_{g+1},\ldots,\Delta T_{g+s}\right]^t \quad (7)$$

and the dependent vector in incremental variables as

$$b=\left[\Delta Q_1,\ldots,\Delta Q_g,\Delta V_{g+1},\ldots,\Delta V_{g+s+1},\ldots,\Delta V_n\right]^t \quad (8)$$

The upper and lower limits on both the control and dependent variables in linearized form are expressed as

$$b^{max}=[\Delta Q_1^{max},\ldots,\Delta Q_g^{max},\Delta V_{g+1}^{max},\ldots,\Delta V_{g+s}^{max},\Delta V_{g+s+1}^{max},\ldots,\Delta V_n^{max},]^t$$

$$b^{min}=[\Delta Q_1^{min},\ldots,\Delta Q_g^{min},\Delta V_{g+1}^{min},\ldots,\Delta V_{g+s}^{min},\Delta V_{g+s+1}^{min},\ldots,\Delta V_n^{min},]^t$$

$$x^{max}=[\Delta T_1^{max},\ldots,\Delta T_t^{max},\Delta V_1^{max},\ldots,\Delta V_g^{max},\Delta Q_{g+1}^{max},\ldots,\Delta Q_{g+s}^{max},]^t$$

$$x^{min}=[\Delta T_1^{min},\ldots,\Delta T_t^{min},\Delta V_1^{min},\ldots,\Delta V_g^{min},\Delta Q_{g+1}^{min},\ldots,\Delta Q_{g+s}^{min},]^t \quad (9)$$

Where

$$\Delta T^{max}=T^{max}-T^{act},\qquad \Delta T^{min}=T^{min}-T^{act}$$

$$\Delta Q^{max}=Q^{max}-Q^{act},\qquad \Delta Q^{min}=Q^{min}-Q^{act}$$

$$\Delta V^{max}=V^{max}-V^{act},\qquad \Delta V^{min}=V^{min}-V^{act}$$

A. Computation of sensitivity matrix (S)

The sensitivity matrix S relating the dependent and control variable is evaluated [7] in the following manner. Considering the fact that the reactive power injections at a bus does not change for a small change in the phase angle of the bus voltage, the relation between the net reactive power change at any node due to change in the transformer tap settings and the voltage magnitudes can be written as

$$\begin{bmatrix}\Delta Q_g\\ \Delta Q_S\\ \Delta Q_r\end{bmatrix}=\begin{bmatrix}A1 & A2 & A3 & A4\\ A5 & A6 & A7 & A8\\ A9 & A10 & A11 & A12\end{bmatrix}\begin{bmatrix}\Delta T_t\\ \Delta V_g\\ \Delta V_s\\ \Delta V_r\end{bmatrix} \quad (10)$$

Then, transferring all the control variables to the right hand side and the dependent variables to the left hand side and rearranging:

$$\begin{bmatrix}\Delta Q_g\\ \Delta V_S\\ \Delta V_r\end{bmatrix}=[S]\begin{bmatrix}\Delta T_t\\ \Delta V_g\\ \Delta Q_s\end{bmatrix} \quad (11)$$

B. Computation of voltage stability objective function ($v_L=\sum L^2$) sensitivities (C) with respect to control variables

The sensitivities of the voltage stability objective function (v_L) with respect to the real and reactive power injections at all the buses except the swing bus (angle reference bus) are first computed and these values are used to compute the objective function sensitivities with respect to the control variables. Considering the fact the real power injection does not change for a small change in voltage magnitude of the bus and the reactive power injection at a bus does not change for a small change in the phase angle of the bus voltage, the relation between the sensitivities of the objective function with respect to the real and reactive power injections at all the buses except the swing (angle reference bus) bus is given by

$$\begin{bmatrix}\frac{\partial v_L}{\partial \delta_2}\\ \vdots\\ \frac{\partial v_L}{\partial \delta_n}\end{bmatrix}=\begin{bmatrix}\frac{\partial P_2}{\partial \delta_2} & \cdots & \frac{\partial P_n}{\partial \delta_2}\\ \vdots & \cdots & \vdots\\ \frac{\partial P_2}{\partial \delta_n} & \cdots & \frac{\partial P_n}{\partial \delta_n}\end{bmatrix}\begin{bmatrix}\frac{\partial v_L}{\partial P_2}\\ \vdots\\ \frac{\partial v_L}{\partial P_n}\end{bmatrix} \quad (12)$$

$$\begin{bmatrix}\frac{\partial v_L}{\partial V_2}\\ \vdots\\ \frac{\partial v_L}{\partial V_n}\end{bmatrix}=\begin{bmatrix}\frac{\partial Q_2}{\partial V_2}V_2 & \cdots & \frac{\partial Q_n}{\partial V_2}V_2\\ \vdots & \cdots & \vdots\\ \frac{\partial Q_2}{\partial V_n}V_n & \cdots & \frac{\partial Q_n}{\partial V_n}V_n\end{bmatrix}\begin{bmatrix}\frac{\partial v_L}{\partial Q_2}\\ \vdots\\ \frac{\partial v_L}{\partial Q_n}\end{bmatrix} \quad (13)$$

Knowing the terms $\partial v_L/\partial\delta$, $\partial v_L/\partial V$, $\partial P/\partial\delta$, and $\partial Q/\partial V$ in the above relation, the sensitivities of the objective function with respect to the real and reactive power injections at all the buses except the swing bus, $\partial v_L/\partial P_k$, $\partial v_L/\partial Q_k$, k=2...n (bus 1 is considered as a reference bus) can be computed. From the solution of the above the objective function sensitivities with respect to transformer taps and generator excitation voltages can be calculated using the equations given below.

$$\frac{\partial v_L}{\partial T_{km}}=\left[\frac{\partial v_L}{\partial P_k}\left(\frac{\partial P_{km}}{\partial T_{km}}\right)+\frac{\partial v_L}{\partial Q_k}\left(\frac{\partial Q_{km}}{\partial T_{km}}\right)+\frac{\partial v_L}{\partial P_m}\left(\frac{\partial P_{mk}}{\partial T_{km}}\right)+\frac{\partial v_L}{\partial Q_m}\left(\frac{\partial Q_{mk}}{\partial T_{km}}\right)\right] \quad (14)$$

$$\frac{\partial v_L}{\partial V_k}=\frac{\partial v_L}{\partial Q_k}\frac{\partial Q_k}{\partial V_k} \quad (15)$$

The values for $\frac{\partial v_k}{\partial Q_{g+k}}$ are obtained from the solution of (13)

C. Computational Procedure

In the day-to-day operation of the power systems, the following are the steps used to obtain the optimal reactive power allocation in the system for improvement of voltage stability.

Step 1: Perform the initial operational load flow (or output of state estimation) to obtain the values of L-index at each load bus and check for voltage violations in the system.

Step 2: Advance the VAR control iteration count.

Step 3: Compute the column matrices (b_{max}, b_{min}) of the linearized upper and lower limits on the dependent variables.

Step 4: Compute the column matrices (x_{max}, x_{min}) of the linearized upper and lower limits on the control variables.

Step 5: Modify the matrices x_{max} and x_{min} to reasonably small ranges.

Step 6: Compute the sensitivity matrix (S), relating the dependent variables and the control variables.

Step 7: Compute the row matrix (C) of the objective function sensitivities with respect to the control variables.

Step 8: Solve the optimization problem using the linear programming technique.

Step 9: Obtain the optimum settings of control variables.

Step 10: Perform the operational load-flow with the optimum settings of the control variables. Find the L-index for all the load buses in the system.

Step 11: Check for satisfactory limits on the dependent variables. If no, go to *step 2.*

V. Results and discussions

The proposed approach has been tested on a 24-node EHV 400kV Indian power system network shown in Fig.1. The system has seven 400/220 kV tap changing transformers, 4 generator buses and 20 other buses. To identify the critical OLTC transformers in the system under peak load conditions only OLTC transformers were used as the control variables.

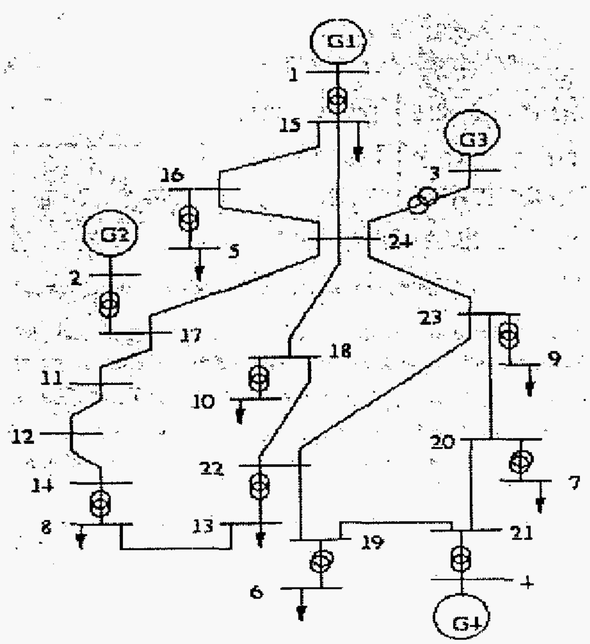

Fig. 1. A Practical system.

Case 1-Effect of tap - controller settings on the system:

In this case, tap setting of each transformer is varied in its full range from lower limit (0.9 p.u.) to the upper limit (1.1p.u.) in steps of 0.0125 by keeping the tap settings of the remaining transformers at nominal value (1.0 p.u.), under peak load conditions. For each tap setting of controlling transformer the power flow solution and voltage stability indices of all the load buses for the system are obtained. The corresponding results of voltage magnitudes and voltage stability indices (L values) are shown in Fig.2 and Fig.3 respectively.

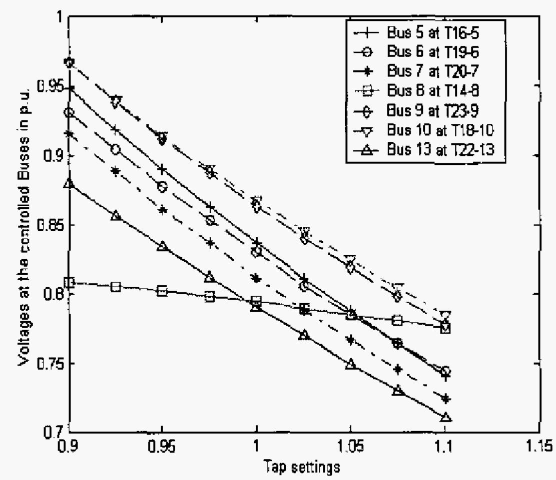

Fig. 2. Voltages at the controlled buses (in p.u.) with respect to tap settings

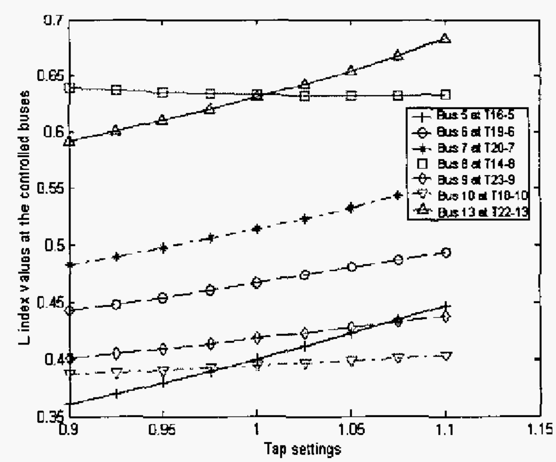

Fig. 3. L index values at the controlled buses with respect to tap settings

From these results it is clear that the effect of tap changing transformer connecting between the buses 14 and 8 (near the load bus 8) is different from other transformers. The voltage at the bus 8 is very low (0.808 p.u.) and the voltage stability index (L index) value is very high (0.639) even at the limit 0.9 tap setting of controlling transformer T_{14-8}.

The effect of tap setting of each transformer on the all generator reactive power outputs is obtained from power flow solution. The results are shown from Fig.4 and Fig. 5 corresponding to Generator G1 and Generator G3 respectively. From these results it is clear that the transformer connecting between the buses 14 and 8 ($T_{14\text{-}8}$) drawing more reactive power from the generators in comparison to other transformers, when the tap is moved from nominal 1.0 towards 0.9 setting. Hence this transformer is critical for the system.

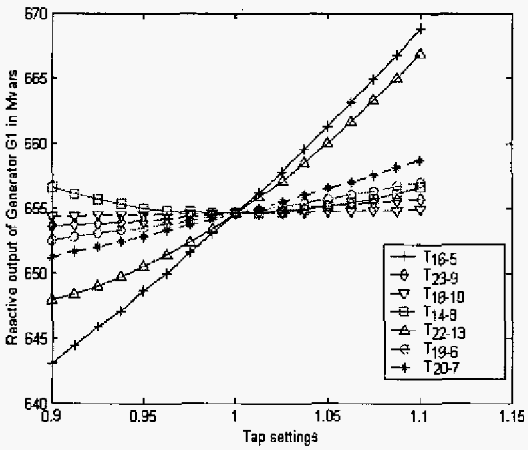

Fig. 4. Reactive output of Generator G1 with respect to various controlling transformers

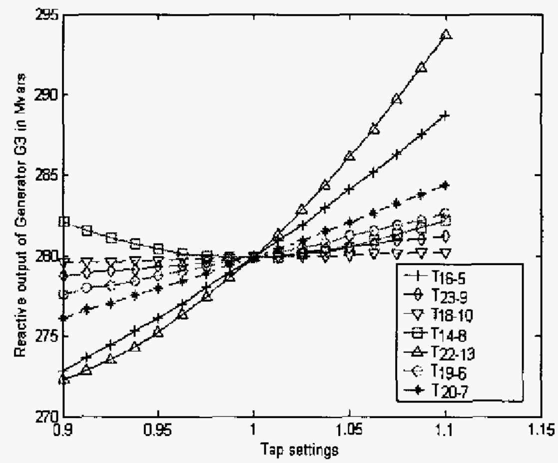

Fig. 5. Reactive Power output of Generator G3 with respect to various controlling transformers.

TABLE I
MOVEMENT OF CONTROLLER SETTINGS DURING OPTIMIZATION

Iteration no.	Transformer Tap settings							$\sum L^2$	Total power loss %
	$T_{16\text{-}5}$	$T_{19\text{-}6}$	$T_{20\text{-}7}$	$T_{14\text{-}8}$	$T_{23\text{-}9}$	$T_{18\text{-}10}$	$T_{22\text{-}13}$		
0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.4217	2.42
1	0.9875	0.9875	0.9875	1.0125	0.9875	0.9875	0.9875	2.3577	2.38
2	0.975	0.975	0.975	1.025	0.975	0.975	0.975	2.2963	2.35
3	0.9625	0.9625	0.9625	1.0375	0.9625	0.9625	0.9625	2.240	2.33
4	0.950	0.950	0.950	1.050	0.950	0.950	0.950	2.1863	2.30
5	0.9375	0.9375	0.9375	1.0625	0.9625	0.9625	0.9375	2.1405	2.29
6	0.950	0.925	0.925	1.050	0.975	0.975	0.925	2.1089	2.27
7	0.9625	0.9375	0.9125	1.0375	0.9625	0.9625	0.9125	2.0798	2.26
8	0.950	0.925	0.925	1.025	0.975	0.975	0.9000	2.0512	2.24

Case 2. Critical OLTC identification using optimization

To identify critical OLTC transformers in the system under peak load conditions only OLTC transformers were used as control variables. Results were obtained using two different objective functions:

- Minimization of voltage deviations from pre-desired values (Objective Vdesired);
- Minimization of the sum square of L-indices for the system (Objective V stability).

Results for the VAR control optimization are presented in Table I. All the transformer taps are at nominal value (1.0) initially. It is observed from the VAR control iterations, that the objective $V_{stability}$ recommends tap variation from nominal 1.0 towards 0.9 at all OLTC transformers except for Transformer between the buses 14 and 8 ($T_{14\text{-}8}$). The optimum movement for the transformer $T_{14\text{-}8}$ tap is from nominal 1.0 towards 1.1. Hence OLTC $T_{14\text{-}8}$ is critical for the system and may be made manual to avoid possible voltage instability due to the operation of the OLTC transformer to improve the voltage at the secondary side of the transformer.

VI. Conclusion

The problem of voltage stability in power system focusing on the effect of On Load Tap Changing transformers is discussed. An approach is presented for monitoring the on – load tap changing transformers effect on voltage stability and identifying the critical transformers which may lead to voltage instability under peak load conditions. The approach is based on voltage stability L- index. The effect of OLTCs on voltage stability are simulated and explained for a 24 – node practical power system.. The studies show that under varying load conditions the OLTC directions obtained with different objectives are similar, if the system conditions are not close to critical voltage instability situation. However, as the system conditions are approaching closure to voltage instability conditions, sensitivities of some critical transformers may be reversed.

VII. References

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VIII. Biographies

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