Modeling and Optimal Placement of Voltage Regulator for a Radial System

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Abstract— **Voltage regulation is an important subject in electrical distribution system. The voltage drop along primary distribution systems has been a crucial operating problem, especially for lengthy feeders, with a significant load concentration at their ends. As the load on a feeder varies the voltage supplied to every customer will also vary. It is the utilities responsibility to keep the customer voltage within American National Standard Institution (ANSI) standard. In order to satisfy the ANSI standard, the utility must have means of regulating the feeder voltage. In view of this, a model of control system for voltage regulator (VR) is developed and tested.**

The paper presents modeling of control system for voltage regulator, which is On-Load Tap Changing (OLTC) transformer. The control system model is developed using MiPower software. The model is tested for 12 bus and 70 bus radial distribution systems. Further a case study is done for optimal placement of voltage regulator for the said systems. The Placement of voltage regulator is done with help of a two different algorithms. These algorithms help to find the location and number of voltage regulator required for systems. Finally comparison of two algorithms is done to select best method for the placement of voltage regulator. The voltage profile of the systems are improved and real power losses occurred for the systems with VR are less. The first algorithm gave good results with respect to reduction of losses and economical aspects.

Keywords- Modelling, Voltage regulators, OLTC

I. INTRODUCTION

Voltage regulation is an important subject in electrical distribution engineering. It is the utilities responsibility to keep the customer voltage within specified tolerances. High steady state voltage can reduce light bulb life and reduce the life of electronic devices. On the other hand, a low steady state voltage leads to low illumination levels, shirking of television pictures, slow heating of heating devices, motor starting problems, and overheating in motors. However, most equipment and appliances operate satisfactorily over some reasonable range voltages; hence, certain tolerances are allowable at the customer end. Thus, it is common practice among utilities to stay within preferred voltage levels and ranges of variations for satisfactory operation of apparatus as set by various standards such as ANSI (American National Standard Institution).

Transformers are often used for control of voltage and reactive power flow. Therefore, practically all transformers used for bulk power transmission and many distribution transformers have taps in one or more windings for changing the turns ratio. Changing the ratio of transformation is required to compensate for variations in system voltages. Two types of tap-changing facilities are provided off-load tap changing and on load tap changing (OLTC). The off- load tap-changing facilities require the transformer to be de-energized for tap changing; they are used when the ratio will need to be changed only to meet long-term variations due to load growth, system expansion, or seasonal changes. The OLTC is used when the changes in ratio need to be frequent for example to take care of daily variations in system conditions. The taps normally allow the ratio to vary in the range of ±10% to ±15%.

VRs are placed in the system with the main objective of minimizing voltage deviation from a nominal value (reference). A first algorithm is two step algorithms for the optimal placement of voltage regulators in distribution system. In the first step, voltage regulators are placed (and the tap position is determined) at candidate buses, aiming at minimizing voltage drops and real power losses. In the second step, an attempt to reduce the number of voltage regulators is made, taking into consideration economical aspects.

The second algorithm is placement of voltage regulators is on the low voltage buses and selection of placement of VR is based on distance. First step is computation of the buses crossing (min/max) voltage limit specified. The buses which cross the limit compute distance from buses to source point and arranging increasing order place voltage regulator at less distance bus from source point. It attempts to minimize the number of initially selected voltage regulators as much as possible, by moving them in such a way as to control the network voltage at the minimum possible cost. Methods are adopted for reduction of distribution losses are installing voltage regulator, HV distribution system, Grading of conductor etc. In this paper losses are decreased by installing voltage regulator. Voltage regulator is basically an auto transformer with number of steps to maintain voltage within specified limits.

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II. MODELING OF ON-LOAD TAP CHANGING TRANSFORMER

A general system block is shown in Fig.1. It consists of the following parts:

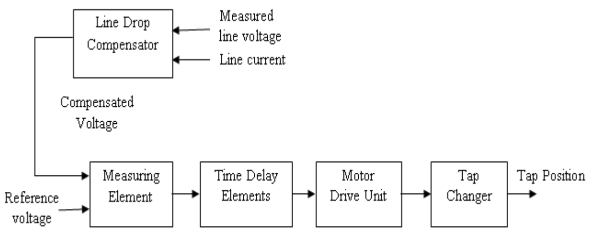

Figure 1. Block diagram of OLTC.

A. *Measuring Transformer*

Both potential (PT) and current (CT) transformers are modeled as ideal, lossless transformers, with their turn's ratios:

B. *Potential transformer [4]*

$$m_{PT} = \frac{V_{2r}}{V'_{2r}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(i)$$

C. *Current Transformer [4]*

$$m_{CT} = \frac{I_{2r}}{I'_{2r}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(ii)$$

D. *Line Drop Compensator*

A line-drop compensator (LDC) is used to correct the reference voltage V2r, with the variation of transformer load. It simulates the voltage drop across an outgoing line connected to the ULTC transformer bus, by introducing the voltage drop on compensator impedance $Z_C = R_C + jX_C$, which should map the line impedance voltage drop. This drop is calculated depending on the type of compensator and voltage regulator connection to the measuring transformers. In principle, the LDC compensates some definite portion K of line-voltage drop, so that the compensator voltage Vc in volts is determined from the expression below [4]

$$V_c = \left|V_t - (R_C + jX_C)I_t\right. \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(iii)$$

$$V_{err} = V_{ref} - V_C \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(iv)$$

V_{ref} is the reference voltage, in pu. V_C is the measuring voltage, after line-drop compensator voltage is added, in pu. Verr is voltage error.

E. *Voltage Regulator Measuring and Time- Delay Elements [4]*

$$V_m = \begin{cases} 0 & for \quad -D \le V_{err} \le +D \\ 0 & for \quad D < V_{err} \le D + \varepsilon; \quad V_{err}\ increasing \\ 0 & for \quad -D - \varepsilon \le V_{err} \le -D; \quad V_{err}\ decreasing \\ +1 & for \quad V_{err} > D + \varepsilon \\ +1 & for \quad D \le V_{err} \le D + \varepsilon; \quad V_{err}\ decreasing \\ -1 & for \quad V_{err} < D - \varepsilon \\ -1 & for \quad -D - \varepsilon \le V_{err} \le -D; \quad V_{err}\ increasing \end{cases}$$

The output of the measuring element is V_m, which takes a value of 0, 1 or -1, depending on the input V_{err}. With a regulator dead band of D and a hysteresis band of ε, the output is V_m is ouput from measuring element.

The time delay element is used to prevent unnecessary tap changes in response to transient voltage variations and to introduce the desired time delay before a tap movement.

The timer unit determines the time duration of the error voltage (V_{err}) exceeding the dead band. The timer is advanced if V_{err} is within the dead band. if there is a tap movement ($V_n \neq 0$) , or if V_{err} oscillates above and below dead band. The output V_d of the time delay unit is normally zero. If the accumulated time T of the timer exceeds TD, then V_d is set to V_m (i.e., 1 or -1) , there by sending a signal to the tap- changer motor to move the tap up and down.

The time delay T_d is equal to T_{d0} for the first tap movement. Some regulators have an inverse time- delay characteristic, in which case the time delay is inversely proportional to the voltage error.

For the second and subsequent tap movements the time delay T_d is equal to T_{dl}. This allows introduction of intentional time delay between consecutive tap movements, if so desired.

F. *Motor- drive unit and tap- changer mechanism[4]*

It may be represented by a simple time delay TM inherent to

$$T_d = \frac{T_{do}}{V_{err}/D} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(v)$$

the equipment. The output signal V_n represents an incremental change in tap position, and is equal to 0, 1, or -1. A change in tap position is reflected in the transformer model as an incremental change in per unit turns ratio. The per unit turns ratio after the i^{th} operation is where Δn represents the per unit turns ratio step corresponding to a change in tap position by one step. The above assumes that the controlled bus is on the secondary side. If the controlled bus is on the primary side, we have Tap- changer position after ith operation completed. The transformer tap-ratio is then expressed as

$$a_i = 1 + n_i \Delta a \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(vi)$$

$$\bar{n}_i = \bar{n}_{i-1} - \Delta\bar{n}(V_n) \ldots\ldots\ldots\ldots\ldots\ldots\ldots(vii)$$

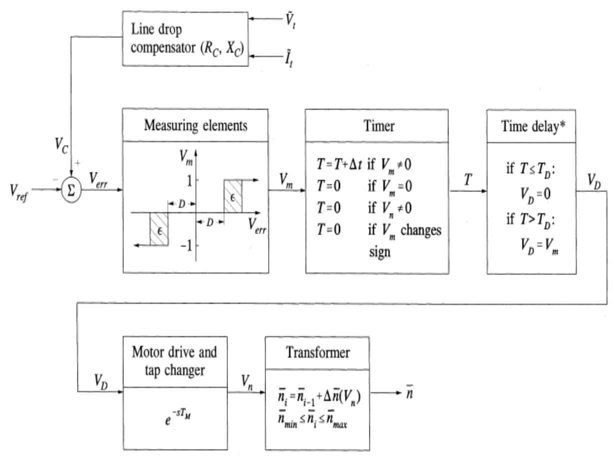

Figure 1.On-load tap changer control system model [5].

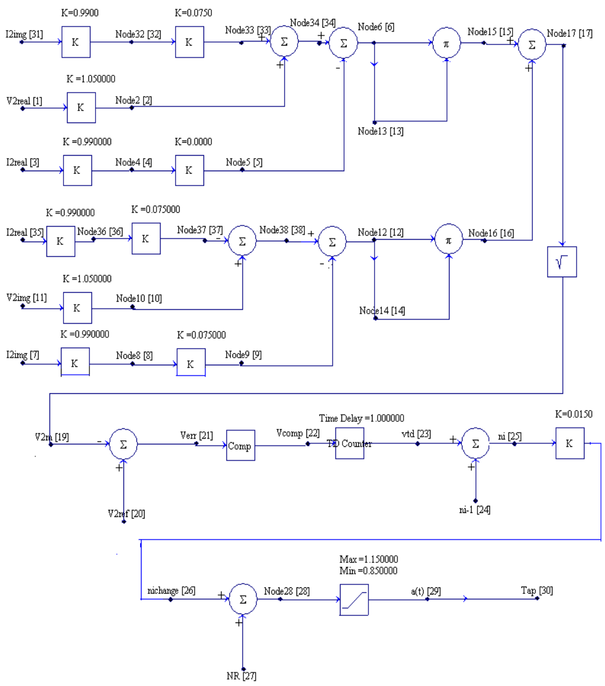

Figure 2. OLTC control system model using MiPower

III. VR PLACEMENT ALGORITHMS

Algorithm1 [4]

Part I: Selection, placement and control of VRs

(A) Compute the operating point through a load flow calculation. Identify the critical paths.

(B) For each critical path do:

(1) Place a VR at the end node of the critical path.

(2) Run a load flow, setting the VR's tap position so as to eliminate the voltage violation at this node.

(3) Compute FT for this configuration.

(4) Move the VR upstream to the next bus of the critical path and go back to step (2).

(5) The procedure is interrupted when the substation bus is reached.

(C) The VR is placed at the bus which resulted in the best FT.

Each load flow is run taking the last solution as a new Starting point, thus reducing the number of load flow iterations. Note that Part I seeks the best alternative based on technical aspects.

Part II: Reduction of the number of VRs

The method proposed in [6] determines possible paths for reallocating VRs in order to minimize the number of VRs. The procedure is described below.

(A) The VRs are moved upstream (towards the substation) as far as no voltage violations are detected. Therefore, each 3VR will have a path, for which voltage regulation is possible.

(B) Path pairs (for each combination of two VRs) are defined.

(C) If there are common buses in the path pairs, one only VR will be placed at the common bus, replacing both VRs initially placed.

The goal of the procedure of Part II is to obtain the best alternative according to economical aspects, by reducing the number of VRs. The voltage drop percentual factor FatV% is expressed by equation (vii) [1] it indicates the quality of a certain configuration in terms of voltage profile.

$$Fat_V\,\% = \frac{\sum_{i=1}^{N}\left(V_{nom} - V_i^{f}\right)^2}{\sum_{i=1}^{N}\left(V_{nom} - V_i^{0}\right)^2} * 100 \ldots\ldots\ldots\ldots\ldots\ldots(viii)$$

Where N is the number of buses, Vnom is the system's nominal voltage, and V_{i0} and V_{if} are the voltage magnitudes at bus i respectively at the initial configuration and at some tentative configuration involving the placement of VRs along the critical path.

Likewise, the power losses percentual factor FatP% is given by equation (ix) [1].

$$Fat_P\% = \frac{\sum_{j=1}^{M} PL_j^f}{\sum_{j=1}^{N} PL_j^0} * 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (ix)$$

where M is the number of branches, and PLj0 and PLj f are the power losses at branch j respectively at the initial configuration and at some tentative configuration involving the placement of VRs along the critical path.

From eq (vii) and (ix) it is possible to define an objective function is given by eq (x) [1] that takes into account the technical aspects described above as

$$FT = (pv.Fat_V\% + pp.Fat_P\%) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (x)$$

Where pv and pp are weights that can be defined as:

- pv = 1 and pp = 0 - whenever voltage drop only is to be considered,
- pv = 0 and pp = 1 - whenever power losses only are to be considered, or
- pv = 0.5 and pp = 0.5 - whenever both aspects are to be considered.

FT is computed for each system configuration during the VR placement procedure. Smaller FTs indicate the best configurations regarding VR placements from the technical standpoint.

Algorithm 2

Step1. For a given single feed system perform load flow.
Step2. Compute the buses crossing (minimum/maximum) voltage limit specified.
Step3. For all the nodes obtained in step 2; compute the distance from nodes to source point and arrange in increasing order.
Step4. Consider first node (i.e. node nearest to source).
Step5. Trace the path towards source and determine next immediate node and check for the line between two nodes.
Step6. If line exist proceed else consider next node and move to step 5.
Step7. Add Transformer (Voltage regulator) at from node of the line connected to concerned node (Node A) with the insertion of dummy bus (D1)
Step8. Initial default values for transformer data should be taken as per table 1
Step9. Now perform the load flow again with voltage regulator (VR) and check buses crossing (min/max) voltage limit specified.
Step10. Now trace the path to the source for the buses crossing (minimum/maximum) voltage limit.
Step11. If from bus of VR placed before is crossed in the path, then trace source path from (from bus of VR placed) to get next immediate bus (Node B).
Step12. Place the VR at Node B with dummy bus (D2) and values as in table 1 and remove previous placed VR if it is line else go to step 5.
Step13. If number of separate lines (eg:2) are going to source point then place same number of VR (eg:2) ; one on each line.
Step14. Repeat from step 9.
Step15. If from bus of VR is not crossed in the path, then check voltage of dummy bus (D2).
Step16. If dummy bus (D2) crosses (maximum/minimum) voltage limit specified.
Step17. Adjust taps such that voltage at dummy bus created, should be less than maximum voltage (p.u) - 0.02 p.u or more than 1 p.u for minimum condition.
Step18. If D2 voltages are within limits; repeat from step 5.
Step19. Stop the program when all bus voltages are within minimum/maximum limits.
Step20. Now the Voltage regulator details can be changed by user and same data can be used for analysis next time.

IV. SIMULATION RESULTS

TABLE I. COMPARISON OF BUS VOLTAGES FOR 12 BUS SYSTEM

Node No	From Name	Voltage(p u) Without VR	Voltage(p u) With VR (al 1)	Voltage(p u) With VR (al 2)
1	Bus 1	0.9800	0.98	0.98
2	Bus 2	0.9606	0.9607	0.9607
3	Bus 3	0.9515	1.0372	0.9516
4	Bus 4	**0.9375**	1.0244	1.0373
5	Bus 5	**0.9304**	1.0179	1.0309
6	Bus 6	0.9537	1.0391	1.0391
7	Bus 7	**0.9485**	1.0344	1.0343
8	Bus 8	**0.9340**	1.0211	1.0341
9	Bus 9	0.9506	1.0363	1.0362
10	Bus 10	**0.9401**	1.0267	1.0266
11	Bus 11	**0.9337**	1.021	1.0339
12	Bus 12	**0.9330**	1.0203	1.0333
13	Dummy Bus 13	-	1.0455	1.0454
14	Dummy Bus 14	-	1.0455	1.05

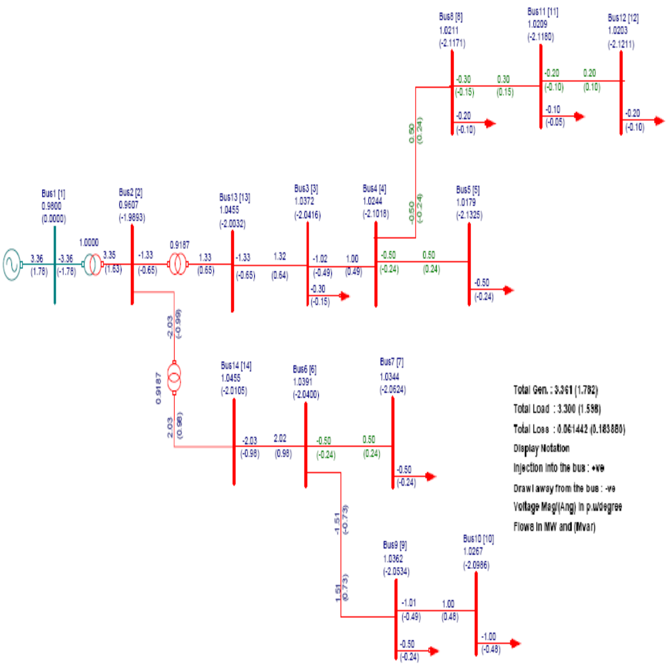

Figure 3. Single line diagram of 12 bus system with VR placement.

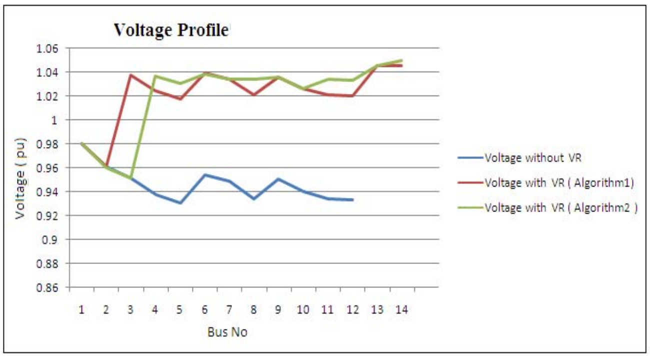

Figure 4. Voltage profile for 12 bus system with VR

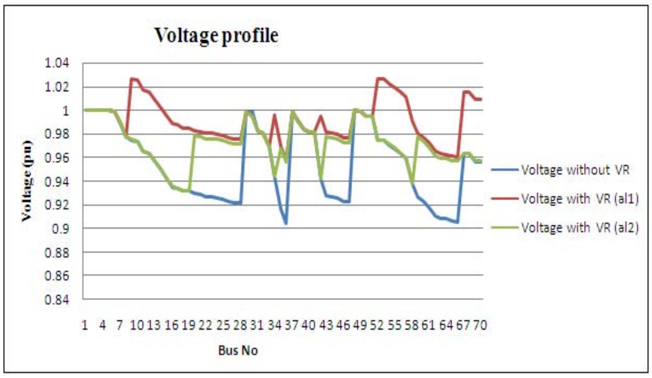

Figure 5. Voltage profile for 70 bus system with VR

TABLE II. COMPARISON REAL POWER LOSSES FOR 12BUS SYSTEM

System description	Peak losses (kW)	Saving (kW)
Without VR	719.26	
With VR (Algorithm 1)	614.40	104.86
With VR (Algorithm 2)	629.22	90.04

TABLE III. COMPARISON REAL POWER LOSSES FOR 70BUS SYSTEM

System description	Peak losses (kW)	Saving (kW)
Without VR	926.84	
With VR (Algorithm 1)	733.30	193.54
With VR (Algorithm 2)	808.23	118.61

V. CONCLUSIONS

The detailed modeling of On-Load Tap Changing transformer and optimal placement of voltage regulator for radial distribution system is presented in this thesis. The modeled control system block for OLTC transformer helps to change the tap position of the transformer automatically depending on change in the load and maintains the voltage within limit. It improved the voltage profile of the system and also contributes to real power loss saving.

The location and optimal adjustments found by the algorithm satisfy the defined criteria. The losses reduction was low, this shows that the main use of voltage regulators is to correct voltage in all feeder buses. The proposed algorithms are tested with two systems consisting of 12 bus and 70 bus radial distribution systems. The results are compared for these two systems using two different algorithms. The results are found to be best for first algorithm compared to second. The first algorithm showed to be efficient, providing adequate alternatives for meeting both technical and economical constraints. It is important to point out that in an ever increasing demand scenario, the appropriate placement of VRs with smaller tap positions is most important.

BIOGRAPHIES

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