INVESTIGATION OF THE IMPACTS OF PRIMARY SUBSTATION'S OLTC ON VOLTAGE REGULATORS PLACEMENT IN DISTRIBUTION SYSTEMS

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ABSTRACT

In this paper, it is attempted to demonstrate the impact of Primary Substation's (PS) On Load Tap Changer (OLTC) on Voltage Regulator (VR) placement problem in distribution systems. As the voltage of primary substation continuously changes because of the tap operation of the OLTC, the voltage changes directly affect the required number and location of VRs from distribution system planning point of view. Therefore in this paper, importance of PS's OLTC modeling is established in order to have reliable and feasible VR placement. Genetic Algorithm (GA) has been utilized to eliminate voltage violations and minimize power losses by placing VRs throughout the whole distribution system. The simulation results insist on the fact that the consideration of OLTC's Automatic Voltage Regulator (AVR) significantly influences the results of the VR placement problem.

INTRODUCTION

OLTCs and VRs are both voltage control devices controlling voltage level of their secondary side in real-time basis directly by changing their tap position. The only difference is that OLTCs work between two voltage levels, whereas similar voltage levels are linked through VRs. On the other hand, off Load Tap Changers (OFF-LTC) are widely used in Secondary Substations (SSs) because of their cheap price considering the fact that they lack real-time tap changing ability. From technical point of view, utilities operating feeders with high load level variations tend to have voltage control flexibility using OLTCs rather than OFF-LTC at SSs whereas from financial perspective, this solution is costly. Instead, few VRs can be mounted along the medium voltage feeder to partially satisfy voltage flexibility need of utilities.The benefits of adding VRs to MV feeders are voltage violation elimination, power loss reduction, hosting capacity improvement etc.

The voltage flexibility achieving from utilization of VRs along a medium voltage feeder depends on the number and location of installed VRs. This voltage flexibility allows utilities to operate the system under various load levels within voltage constraints. Apart from obeying the voltage limits, power loss reduction benefits may also be achieved by VR placement depends on the load model of the customers [1]. If load model of customers is constant power, boosting the voltage level by VRs results in power loss reduction whereas voltage rise done by VRs causes power loss augment for constant impedance loads [2].

By taking advantage of GA's features in term of matching discreet and nonlinear problems [3, 4], it is used to optimize the number and location of VRs in this paper. It should be mentioned that, as voltage magnitude of all MV buses are affected by OLTC's tap operation in PS, the impact of OLTC in optimum number and location of VRs is the contribution of this paper.

In the following, one of the main voltage control strategies for voltage regulation of OLTC's secondary side (medium voltage (MV)) is presented because this control strategy will be used in scenario 2 of simulation results section.

The voltage control strategy is constant voltage control. Reference voltage (Vref) is kept constant at a certain value (i.e. 1.02 p.u.). A dead band (DB) is defined such a way that Vref placed in the middle of DB as shown in Fig. 1. Tap operation is needed either the voltage of OLTC's secondary side falls below the minimum value of dead band or exceed the upper value of dead band. For instance, with values equal to 1.02 p.u. and 0.02 p.u. for Vref and DB respectively, if secondary side voltage of OLTC becomes less than 1.01 p.u., tap will be operated in order to restore the voltage.

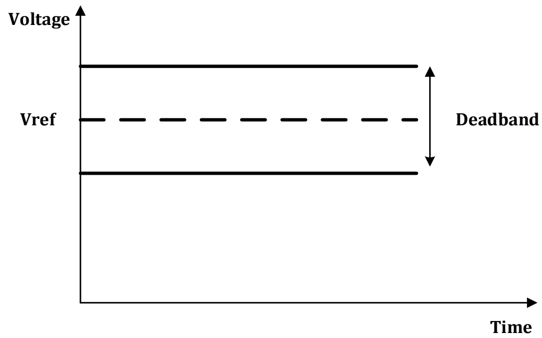

Fig. 1. Setting of OLTC's AVR

Up to now, one of the main voltage control strategies of OLTCs was discussed. In this paper, it is claimed that OLTC's consideration influence VR placement problem. Therefore, unlike references [5-8] which ignore the impact of PS's OLTC on voltage regulator placement problem, OLTC's tap operation will be taken into account in VR placement in this paper.

PROBLEM FORMULATION

The developed formulation for investigation of the impacts of primary substation's OLTC on voltage regulators placement in distribution systems is as follows [9]. Equations (1) to (3) represent the Total Energy Losses

Reduction Benefit (TELRB), the Cost of Voltage Regulators (COVR) and the Total Maintenance Cost (TMC), respectively. The developed objective function which it should be maximized is presented in (4). The net present value factor is calculated by (5). Equations (6) to (8) model branches' current constraints, buses' voltage constraints, and voltage regulators' current constraint, respectively.

$$TELRB = \sum_{n=1}^{N_Y} (CF)^n \left(\sum_{i=1}^{N_L} K_e^i T_i \left(P_{lossB}^{i,n} - P_{lossA}^{i,n} \right) \right) \tag{1}$$

$$COVR = \sum_{i=1}^{N_{reg}} (Cost_i) \tag{2}$$

$$TMC = \sum_{n=1}^{N_Y} \left((CF)^n \sum_{i=1}^{N_{reg}} Maint_{i,n} \right) \tag{3}$$

$$OBJ = TELRB - COVR - TMC \tag{4}$$

$$CF = \left[\frac{\left(1 + \frac{a}{100}\right)}{\left(1 + \frac{p}{100}\right)} \right] \tag{5}$$

$$I_{i,j,n} \le I_i^{max}, \quad \forall i \in \{1,2,\ldots,N_{branch}\}, \forall j \in \{1,2,\ldots,N_L\}, \forall n \in \{1,2,\ldots,N_Y\} \tag{6}$$

$$V^{min} \le V_{w,j,n} \le V^{max}, \quad \forall w \in \{1,2,\ldots,N_{bus}\}, \forall j \in \{1,2,\ldots,N_L\}, \forall n \in \{1,2,\ldots,N_Y\} \tag{7a}$$

$$V^{min} = 0.95 \tag{7b}$$

$$V^{max} = 1.05 \tag{7c}$$

$$I_{k,j,n}^{reg} \le I_k^{\max(reg)}, \quad \forall k \in \{1,2,\ldots,N_{reg}\}, \forall j \in \{1,2,\ldots,N_L\}, \forall n \in \{1,2,\ldots,N_Y\} \tag{8}$$

In the above equations, N_Y, N_L, and N_{reg} are the planning horizon length (year), the number of load levels, and the number of voltage regulators, respectively. K_e is the rate benefit for power loss reduction in $\frac{\$}{kWh}$. $P_{lossB}^{j,n}$ and $P_{lossA}^{j,n}$ are the power losses of j^{th} load level in the n^{th} year before and after VR placement in terms of kW, respectively. $Cost_i$ is the cost of field implementation of the i^{th} VR. T_i is the duration of i^{th}load level per hour. $Maint_{i,n}$ is the maintenance cost of the i^{th} VR in the n^{th} year. V^{min} and V^{max} are the lower allowable limit of voltage and the upper allowable limit of voltage, respectively. $I_{k,j,n}^{reg}$ is The magnitude of the flowing current through the k^{th} voltage regulator in j^{th}load level and in n^{th} year. $I_k^{\max(reg)}$is the maximum allowable current of the k^{th} voltage regulator. N_{bus} and $N_{branch}$are the total number of buses and the total number of branches in the distribution system. $V_{w,j,n}$ is the voltage magnitude of w^{th} bus in j^{th}load level and in n^{th} year. $I_{i,j,n}$ is the magnitude of the current flowing through the i^{th} branch in j^{th}load level and in n^{th} year. I_i^{max} is the maximum allowable current of the i^{th} branch.

SIMULATION RESULTS

VR placement is practiced on a 70-bus distribution system [5], Fig. 2. Two different scenarios are considered to highlight the effect of PS's OLTC on VR placement. It is a fact that voltage of PS is dependent on the control algorithm of OLTC located at PS. Therefore, it is aimed to highlight the importance of control strategy of Automatic Voltage Regulator (AVR) governing tap operation of OLTC in the following.

To investigate the impacts of OLTC on VR placement problem, the control algorithm using for tap movement should be specified. OLTC's impact on feeder's voltage was ignored [5-8] which means the voltage at bus number 1 is considered constant. This approach will be examined by scenario 1 in order to enable us to understand the difference when OLTC's operation is considered in scenario 2. Afterward, impact of OLTC can be taken into account by adding AVR's control algorithm into GA optimization process. To do so, scenario 2 which consider the OLTC's tap operation will be taken into account.

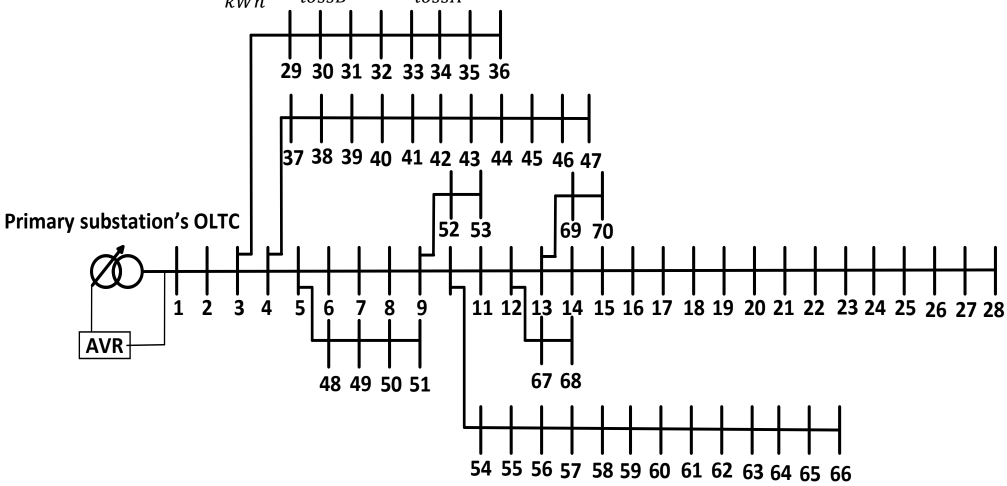

Fig. 2. One-line diagram of under-study distribution system

Scenario 1: fixed voltage at PS

In this scenario, it is assumed that medium level voltage of PS is always fixed at the value of 1.02 p.u.. It means that the tap operation of OLTC at PS has been ignored because it is almost impossible to keep the voltage of PS at a fixed value by tap operation of OLTC. Fig. 3 illustrates the voltage of all buses during the planning horizon which is 20 years. The voltages are in acceptable range. From this figure, it is also clear that the voltage of bus 1 (PS bus) is fixed at the value 1.02 p.u.. Five VRs are installed at buses number 31, 32, 33, 41, and 58.

Scenario 2: constant voltage control

In this part, the operation of OLTC's AVR has been considered in a way that *Vref* and AVR's DB are defined. *Vref* is 1.02 p.u. and DB is 0.02 p.u.. Fig. 4 illustrates the voltage magnitude of the under-study distribution system. Voltage of bus 1 (secondary side of OLTC) is varying inside the DB which is between 1.01 and 1.03 p.u. Ten VRs are used to maximize OBJ by the GA. Ten VRs are installed at buses number 11, 30, 31, 32, 33, 34, 40, 41, 56, and 57.

Comparison of scenarios

The difference between the number and location of VRs in previous scenarios implies the fact that PS's OLTC significantly affect VR placement problem. In scenario 1, OLTC's impact was ignored by considering fixed value for PS's voltage. In scenario 2, OLTC's tap operation was regarded such a way that it reacted for voltages less than 1.01 p.u. and voltages more than 1.03 p.u.. From financial perspective, the results of two scenarios are shown in Table I. By comparing their OBJ, the significant impact of OLTC is evident. For instance, if voltage of PS is considered constant (scenario 1), the OBJ value is $105,507 whereas the OBJ equals to $667,870 for scenario 2 where voltage of PS is changing inside the DB. Therefore ignorance of OLTC's operation in VR placement creat completely different and infeasible results.

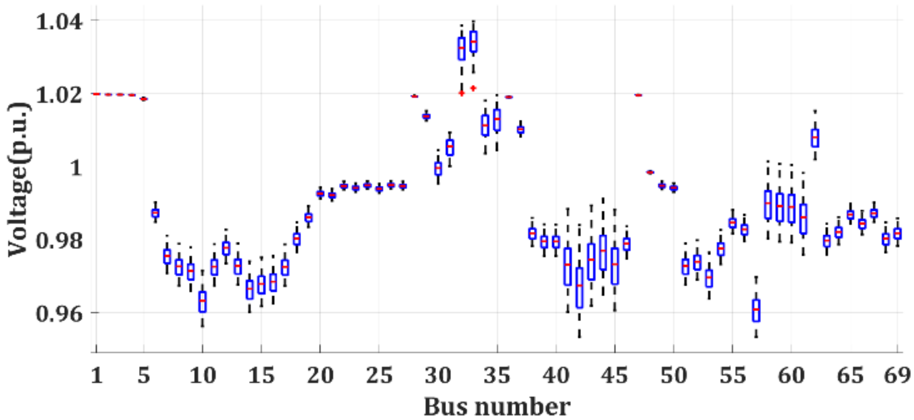

Fig. 3. Voltage profile of scenario 1

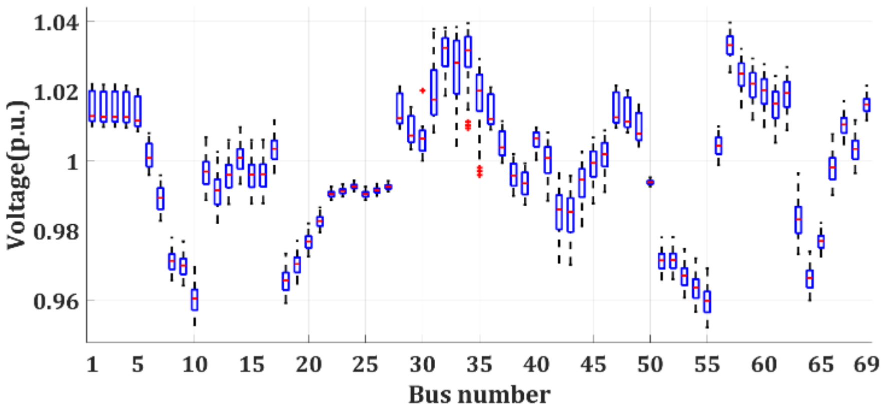

Fig. 4. Voltage profile of scenario 2

Table I
RESULTS OF TWO SCENARIOS

Scenario	TELRB ($)	COVR ($)	TMC ($)	OBJ ($)
1	299,290	148,440	45,343	105,507
2	1,004,200	296,880	90,540	616,780

CONCLUSION

The impact of OLTC's tap operation at primary substation on the voltage of downstream buses is significant in distribution systems. Therefore, control algorithm of OLTC's AVR has to be regarded for solutions such as voltage regulator placement that aim to eliminate voltage violations. In the first scenario, voltage of primary substation is considered constant which means tap operation of OLTC has been ignored because tap movements of OLTC always leads to voltage change at primary substation and downstream buses. In the second scenario, OLTC's tap operation has been considered by defining the reference voltage and dead band for OLTC's AVR. From technical perspective, the number and location of VRs are different in scenario 1 and 2. In addition, objective function as a financial criterion is also different between two scenarios. Therefore, based on the achieved results, ignorance of OLTC's operation at primary substation for VR placement is not valid and it leads to misplacement of VRs and miscalculation of net profit of DSO. For VR placement studies, it is recommended to consider the voltage control algorithm of the OLTC's AVR available at PS. Impact of OLTC's control algorithm including Line drop compensation (LDC) on VR placement can also be studied in the future studies of this paper.

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