Modeling of Automatic Local Controllers in Three Phase Load Flow Calculation

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Abstract — **This paper describes the modeling of automatically operated local controllers, based on the scheduled, measured or calculated values of the locally affected network equipment in real time operation of Distribution Management System – Control Center. The model presented is operated in unbalanced, unsymmetrical distribution networks and analyzed in phase domain. Simulated Locally controlled equipment includes various types of Transformer on load tap changers (LTC), Voltage Regulators and Shunts (Capacitors and Reactors). The modeling considers all control parameters with the special consideration of different phase types of the equipment and measurements, transformer connection types, and operation in unbalanced networks. As an addition to previous works in this area, specific and practical problems and considerations to Capacitor flow control, LTC reverse control with Distribution Generation, Parallel and Looped transformer operation are presented.**

Index Terms—**Voltage regulators modeling, Power regulators, Auto-reversible actions**

I. INTRODUCTION

Local Controllers simulation is an integral part of state estimator and power flow applications in Real-time Distribution Management System Control Center. It is a simulation of automatically controlled on Load Tap Changer (s) and capacitor shunts, which are operated in the field. LTC (s) regulate the voltages on controlled buses, most usually the ones a transformer is immediately connected to, but rarely also, remote buses, or virtual ones compensated by the line voltage drop. Shunts can control voltage or flow. Flow is most usually defined by the reactive power flow through an immediately connected line, but can also be controlling the current or power factor on the line. For some of those controllers there exist telemetered measurements of the exact tap position in case of LTC or number of switched capacitor banks, but for those where this is not known, simulation must provide the values, based on which power flow is calculated.

Voltage drop on a radial distribution feeder carrying power from substation to load is inevitable. Based on past experience in electrical utilities, limits are set for voltage in substation feeders. Voltage should not drop below minimum at peak load condition and it should also not exceed maximum under light load condition. The main purpose of setting up LTC(s) at substation transformers is to maintain the voltage at the feeder head within limits so that voltage along the feeder and at the loads is as desired. The increase or decrease of voltage at the feeder head is dependant on the loading of the feeder and should be able to handle all kinds of loading situations. Various factors, such as voltage measured at local and remote point is taken into account by the voltage regulators before moving the tap up or down [6]. In power flow algorithm multiple tap position changes are simulated until the voltage is in desired limits.

Loads connected to a distribution feeder have active and reactive power demand. The reactive power can be either supplied from the substations or compensated by connecting capacitors to the feeder. Ideally all the capacitors can not be left connected to the feeder all the time. The reason for the same being the reactive power supplied by the capacitors varies as a square of the voltage and may lead to over or under compensation at high or low voltage conditions [4] [6]. Therefore capacitors are connected in banks or switched off dependent on time schedule, drop of voltage, flow of reactive power etc. Some capacitors are equipped with capacitor controllers which may depending on the demand of voltage and reactive power switch in or take out banks of capacitors. Such controls are also simulated in power flow algorithm providing a composite solution to the problem of voltage regulation in distribution systems.

As described above voltage regulation is employed to handle radial flow of power from substation to the load along the feeder. The normal operating conditions are changed for the voltage regulators, in case of reverse flow of power, e.g. presence of a generator on the controlled bus. As the slope of voltage changes and auto-reversible voltage regulation actions are required to handle such conditions.

This paper is divided into four sections. In the 1st section the modeling of the voltage regulators and the capacitors controllers in distribution networks and the simulation of the same in power flow algorithm is described. The actions taken to simulate the changes of local controllers keeping the power flow model intact is described in the 2nd section. In the 3rd section the problems related to loop-parallel topology and back feed (which leads to reverse flow) in the network are discussed. The test results on some practical network conditions are presented in the 4th section.

II. VOLTAGE REGULATORS MODELING

Voltage regulators and LTC(s) are typically constructed as autotransformers with automatically adjusting taps. The

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controls measure the voltage and load current, estimate the voltage at the controlled bus point, and trigger the tap change when the estimated voltage is out of bounds. These controllers are modeled taking into account voltage limitations, granularity of each step and a bandwidth of the controller.

A. Regulators Modeling

Voltage regulation can be defined simply as a function which takes certain input parameters available from field and based on the properties of the transformer to provide an output to keep the voltage on the controlled bus in the desired range [2]. It is an integral part of power flow algorithm as it keeps the voltage on the controlled buses regulated so that the substation does not face a blackout. This function is represented in Eq. 1.

$$V_{DES} = f(V_{SET}, I_{SET}, Z_{SET}, V_{Meas}, I_{Meas}) \quad (1)$$

As described above this function has parameters based on the input data of the transformers and the regulated buses, they are cited by subscript $_{SET}$ and the parameters based on actual field values are cited by subscript $_{Meas}$. The field values are obtained from SCADA (Supervisory Control and Data Acquisition).

The voltage regulators can be broadly categorized into two types.

- Controllers maintaining pre-defined fixed voltages (LTC s), voltage regulator at the substation transformer.

$$V_{DES} = const \quad (2)$$

- Controller with line drop compensation (SVR s) employed along the feeder, where the desired voltage is calculated using eq. 3. The desired voltage in this case has to be in between the minimum and maximum value.

$$V_{DES} = V_{SET} + (R_{SET} + jX_{SET})I_{calc} \quad (3)$$

The main objective of including local controllers in Power Flow is to maintain the desired voltage on the controlled buses in close range to the measured voltage. Under normal conditions these two voltages can be never equal [2]. The algorithm tries to maintain the difference lesser than the threshold, represented in Eq. 4.

$$|V_{DES} - V_{calc}| < \delta \quad (4)$$

The algorithm of voltage control is not a part of the 1st power flow calculation. After the 1st power flow calculation the calculated voltage (calculated by power flow) at the controlled bus is obtained and it is compared with the desired voltage at the bus. Depending on whether the calculated voltage is greater or lesser than the desired voltage the tap position is either moved up or down to bring the voltage near to the desired voltage.

The algorithm can be described in the following steps:

Step I: Power Flow is solved without local controllers simulation purely based on available load values available from load curves.

Step II: The calculated voltages at the controlled buses are obtained from the 1st power flow calculation for each phase.

Step III: In case the network has line drop compensation also, the currents calculated through the transformers are also used for simulation of voltage regulators.

Step IV: The desired voltage is obtained. The desired voltage in case of LTC s are fixed and that in case of line drop compensators are calculated based on the impedance of the line segment and the current calculated at step I.

Step V: The desired voltage is compared with the calculated voltage at every controlled bus for each phase. Based on Eq. 4 it is decided whether the controllers have to act in the next iteration or not, i.e. if the difference is less than the threshold then there is no need for voltage regulators regulating this bus to act. However if the difference is more than the threshold the voltage regulators start acting.

Step VI: The number of tap positions UP or DOWN for the transformer are determined using eq. 5 and 6.

If $V_{DES} > V_{calc}$, direction of tap movement is UP if the local controller is on the same side as the controlled bus and DOWN otherwise.

$$N = \left(V_{DES} - V_{calc} - \delta\right) / StepSize \quad (5)$$

If $V_{DES} < V_{calc}$, direction of tap movement is DOWN if the local controller is on the same side as the controlled bus and UP otherwise.

$$N = \left(V_{calc} - V_{DES} + \delta\right) / StepSize \quad (6)$$

Step VII: Power Flow is calculated again with the adjusted tap positions and the checks for the controlled buses are done again after each iteration step as described from Step IV onwards. Simulation of voltage regulators is finalized when the voltage difference (between desired and calculated voltage) at each controlled bus is below the specified threshold.

B. Capacitor Controllers

Capacitor controllers though simpler than voltage regulators to be simulated in power flow model, do play an important role in regulating voltage and reactive power in distribution systems [3]. They come into action, i.e. they are switched on, when voltage (V) is below the minimum specified value and are switched off when they are above the maximum specified value. Loads present on a feeder consume reactive power (Q), to avoid excessive flow of reactive power through the feeder; capacitors are switched in to compensate for the reactive power consumed by loads. Some capacitors are auto-switched in the network. It is known from historical information that at certain hour in day or night, the requirement of reactive power increases in the network and that certain capacitors has to be switched on [3]. These capacitors are not simulated by power flow algorithm, but are handled during creation of the subsystem model.

As described above capacitor controllers take the following actions in distribution systems:

- *Control Voltage*

  If, $V_{calc} < V_{\min}$, then capacitor is switched ON, else if $V_{calc} > V_{\max}$, capacitor is switched OFF.

- *Control Reactive Power*

  If, $Q_{calc} < Q_{\min}$, then capacitor is switched ON, else if $Q_{calc} > Q_{\max}$, capacitor is switched OFF.

The difference of minimum and maximum settings is much higher than the change of V or Q brought in by the capacitor. This prevents controller oscillations.

III. Voltage Regulators Modeling Actions

As described in the previous section in order to make voltage regulations the tap positions of the transformers need to be changed. This automatically affects the impedance of the transformer. The admittance matrix is factorized only once at the beginning of the power flow calculation [2]. In case of simulation of voltage regulation in each iteration step of power flow this admittance matrix has to be factorized all over again. This can be avoided in case fictitious currents are injected to both sides of the transformer, to keep the initial transformer modeling intact.

A. Transformer Modeling Actions

The initial modeling of transformers has to be changed to as it is shown in Fig. 1 on the left side. Where, T , is the final tap position and Δt is the change in the tap position [2].

$$T = t + \Delta t \tag{7}$$

If the changes in the tap positions are directly represented in the transformer modeling then the transformer admittance matrix needs to be factorized after every iteration step. Instead fictitious currents I_K and I_M are added to nodes K and M . The calculation of these currents is represented in Eq. 8.

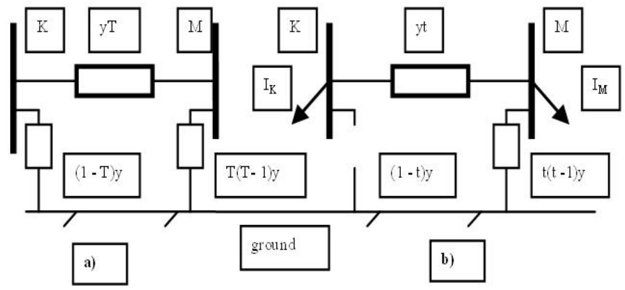

Fig. 1 a) Transformer modeling with and without fictitious currents b) with fictitious currents

$$\begin{aligned} I_K &= -V_M \Delta t\, y \\ I_M &= \left(V_M\left(2t + \Delta t\right) - V_K\right)\Delta t\, y \end{aligned} \tag{8}$$

B. Capacitor Modeling Actions

In some cases capacitors are modeled as banks. A special local controller action is required to switch in more number of banks into action or switch out some banks. The minimum and the maximum number of banks available are specified by input data. The banks are switched in one by one after every checking the calculated values by power flow after every single switching action.

Similar to transformers adding more banks or removing some changes the impedance of the capacitors and directly implementing this in the power flow model shall lead to factorization of the admittance matrix at each step. This situation needs to be avoided. To do the same a fictitious current represented in Eq. 9 is injected to the capacitor to compensate for the change in admittance.

$$I_{cap} = V\left(\Delta Y_{cap}\right) \tag{9}$$

IV. Voltage Regulators- Auto reversible actions

The general rule to decide the controlled bus in distribution systems for voltage regulators is “LTC regulates voltage according to the direction of flow.” Under normal conditions in distribution systems the power flows generally in a transformer from the high voltage to the low voltage side [5]. The LTC(s) work properly when the controlled bus is connected to the low voltage side of the transformer and the SVR also normally control voltage on the bus connected opposite to the side of the source of power. The normal operating conditions for SVR and LTC is shown in Fig. 2.

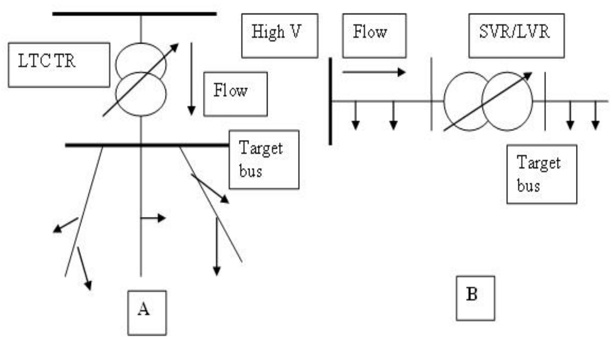

Fig. 2 A) Normal operation for LTC B) Normal operation for SVR

The conditions described favor LTC and SVR to work normally and without problems. Sometimes the functioning of the voltage regulators is challenged by the abnormal conditions caused by network re-configuration in distribution systems e.g. back feed or a generator connected to the controlled bus. This causes power to flow in the opposite direction i.e. to the opposite to the direction of regulation [5].

The LTC and SVR installed at such locations are generally able to recognize the direction of flow and change the regulation direction accordingly. This leads to a simple conclusion that in power flow upon reverse flow should change the controlled bus to the opposite side of the source of the flow. This solution is represented in Fig. 3.

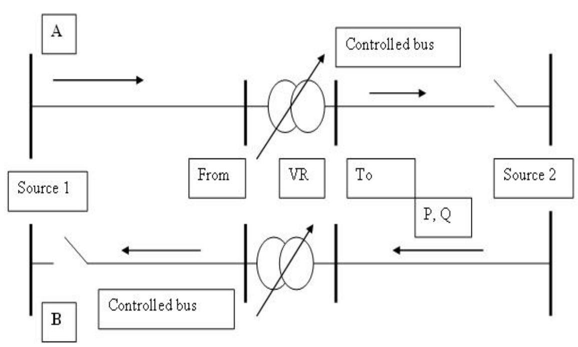

Fig.3 A) Normal control direction B) Control direction in case of reverse flow.

The above stated rule is not always applicable to power flow model. The reason for the same being that directional rule under real conditions can not be always applied. In case the reverse flow is caused by a generator modeled as a PV generator (fixed real power injection and fixed voltage magnitude, reactive power injection and voltage phase angle can change), the directional rule can be applied and the controlled bus can be changed based on the change of the direction of flow. On the other hand if the generator is modeled as a PQ generator (fixed active and reactive power injection, voltage magnitude and phase angle can change), i.e. a negative load, the directional rule is not applicable anymore. As the "FROM" bus in Fig. 3 is not normally controllable anymore, incase of radial and loop/parallel topology different approaches are used to do voltage regulation.

A. Radial Topology

In case of radial topology the bus where the flow of power is always in one direction the controlled bus should be always be opposite to the source of power. The voltage on the slack bus or the supplying bus has to be held constant. And the voltage on the opposite terminal bus should be regulated by LTC, SVR.

B. Loop/Parallel Topology

Loop-parallel topology or presence of PV buses in network might cause voltage at both terminals of the transformer. In this case power flow algorithm has to change tap positions on trial basis keeping voltage at one bus constant at one time. This might sometimes lead to tap positions being set to unrealistic values and may even result in divergence.

V. TEST CASES

IEEE 13 is chosen as the test network, in order to test and present results for the above mentioned modeling of voltage regulators in an unsymmetrical network. IEEE 13 test network is presented in Fig. 4.

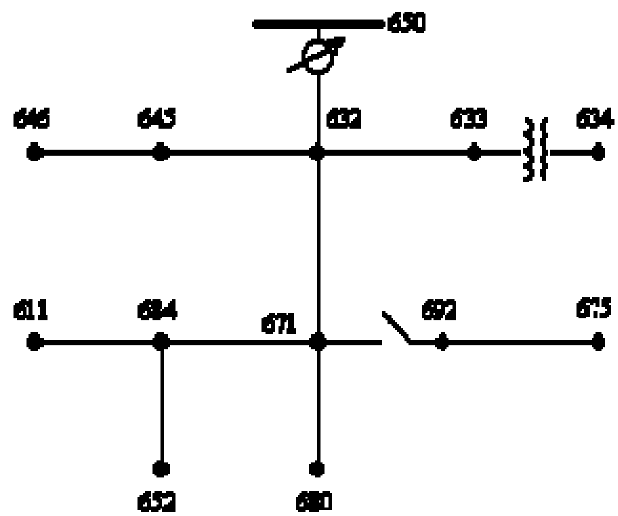

Fig.4. IEEE 13 Test Network

Power flow is calculated on IEEE 13 test network with voltage regulator simulation. The calculated voltages and angles at buses are presented in the Table 1. The final tap positions are presented in Table 2.

As it can be observed, the voltage profile is held almost constant over the span of feeders avoiding any sudden voltage drops. The goal of voltage regulation is to maintain good voltage profile over the span of the feeder, independent of topological conditions and loading of the feeder.

NODE	MAG			ANGLE	MAG			ANGLE	MAG			ANGLE
	A-N				B-N				C-N			
	IEEE Results		Test Results		IEEE Results		Test Results		IEEE Results		Test Results	
650	1	0	1	0	1	-120	1	-120	1	120	1	120
RG60	1.0625	0	1.0625	0	1.05	-120	1.05	-120	1.0687	120	1.0687	120
632	1.021	-2.49	1.011	-2.69	1.042	-121.72	1.03	-119.72	1.0174	117.83	1.02	116.83
633	1.018	-2.56	1.01	-2.87	1.0401	-121.77	1.02	-121.56	1.0148	117.82	1.01	117.82
XFXFM1	0.9941	-3.23	0.98	-3.43	1.0218	-122.22	1.011	-122.22	0.996	117.45	0.996	117.35
634	0.994	-3.23	0.97	-3.03	1.0218	-122.22	1.0108	-122.22	0.996	117.64	0.996	117.34
645					1.0329	-121.9	1.0329	-121.9	1.0155	117.96	1.03	117.86
646					1.0311	-121.98	1.0311	-121.48	1.0134	118.1	1.02	117.9
671	0.99	-5.3	0.99	-5.23	1.0529	-122.34	1.0489	-121.98	0.9778	115.99	0.98	116.02
680	0.99	-5.3	0.98	-5.33	1.0529	-122.34	1.0487	-122.04	0.9778	116.02	0.978	116.02
684	0.9881	-5.32	0.971	-5.32					0.9758	115.92	0.974	114.92
611									0.9738	115.78	0.973	116.78
652	0.9825	-5.25	0.9725	-5.15								
692	0.99	-5.31	0.98	-5.25	1.0529	-122.34	1.0579	-122.84	0.9777	116.02	0.9707	116.02
675	0.9835	-5.56	0.981	-5.56	1.0553	-122.52	1.0563	-121.92	0.9758	116.03	0.968	116.03

TABLE 1: VOLTAGES AT NODES

Regulator	Phase	Voltage at Node 632	TAP
RG60	A	1.011	10
	B	1.05	8
	C	1.0687	11

TABLE2: VOLTAGE REGULATOR RESULTS

VI. CONCLUSION

Regulation of voltage is an important aspect of DMS systems. Operators at utilities demand intelligent regulation to cater to big distributed networks. The algorithms described in this paper, enable a seamless voltage regulation along with volt/VAr control in DMS systems. The current algorithm has good performance and is robust to different topological and loading conditions.

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