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Modeling and Application of Step Voltage Regulators in Radial-Meshed Networks

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***Abstract*—In this paper a three-phase power flow for radial-meshed distribution systems considering different models voltage regulators is analyzed. In fact we study the effect of voltage regulator on radial-meshed network. A voltage regulator is equipment that maintains the voltage level in a predefined value in a distribution line. The 34 bus IEEE test feeder is considered for test. Also, the load flow method is direct solution algorithm.**

***Index Terms*—Step voltage regulators, IEEE test feeders, direct solution algorithm.**

I. INTRODUCTION

The most important tools that engineers used for simulation and then planning the power system is load flow and one important tool that is used to deliver proper service voltages to the customer is step voltage regulator. The loading of a system, results in current flow through all of the system components. This current flow results in a voltage drop as the current passes through the system element. The voltage of buses must be justify with ANSI standards (that pointed to them in table 1) [2], where rang A is rang of normal steady state voltages, rang B is rang of emergency steady state voltages, service voltage is the voltage at the beginning of the feeder or at the substation and utilization voltage is the voltage at the line terminals, or the voltage used by the equipment.

TABLE I: ANSI STANDARDS

	service voltage		utilization voltage	
Type	Min	Max	Min	Max
Rang A	114 (-5%)	126 (+5%)	110 (-8.3%)	125 (+4.2%)
Rang B	110 (-8.3%)	127 (+5.8%)	106 (-11.7%)	127 (+5.8%)

The two critical voltages are the “Maximum Utilization Voltage” and the “Minimum Service Voltage”. Both of these voltages are measured at the customer’s meter. The “Maximum Utilization Voltage” will be the meter voltage at the customer closest to the substation. Typically this voltage is measured at the meter when the customer has no loads on. This implies that there is no voltage drop through the transformer, secondary and service drop. The “Minimum Service Voltage” will occur when the customer has the maximum load on and will include the transformer, secondary and service drop voltage drops.

If we consider base voltage on 120 volt and we regulate the voltage of first of feeder on126 volt(because maximum service voltage is 126 volt), When running a power flow study that models down to the primary of the distribution transformers all voltages must lie between 126 and 120 volts. The direct solution load flow is used in this paper [1] because Distribution networks, with their radial configurations and wide ranging resistance and reactance values, are inherently ill-conditioned and conventional Newton-Raphson and fast decoupled load flow methods are inefficient in solving such networks and this method is suitable for simulation of the radial-meshed network.

In this paper 34 bus IEEE test feeder is modify to radial-meshed network and because it is different from conventional 34 bus IEEE test feeder ,we do not consider previous step voltage regulator type and place of them. With use of method that is used in [4] we specify the place of step voltage regulator. Step voltage regulator is used in three phase type.

Three phase regulators are in three types implemented: wye-connected regulator, open delta-connected regulator and closed delta-connected regulator. For the open delta-connected regulator, two mono-phase regulators are connected in two of the three system phases. Output voltages in this case are line voltages. The open delta-connected regulator only modifies of the three system voltages. Two maximum regulations of the wye and the closed delta regulators are 10% of the nominal voltage of controlled bus. For closed delta-connected regulators the maximum regulation is15%.

II. METHOD OF SIMULATION OF RADIAL-MESHED

Distribution networks having both radial and meshed lines can be solved using the proposed method by breaking the meshes. Fig. 1. (a) shows a typical distribution network that has both radial and meshed lines. Fig. 1. (b) shows the equivalent radial system after breaking the meshed nodes.

$$V_S = Z_C(i_{l1} + i_{l2}) + Z_{line1} \times i_{l1} + Z_l(i_{l1} + i_{l2})$$
$$V_S = Z_C(i_{l1} + i_{l2}) + Z_{line2} \times i_{l2} + Z_l(i_{l1} + i_{l2}) \quad (1)$$

where Z_C, Z_{line1} and Z_{line2} are the impedances of common path of current, line1 and line2. Z_1 is the load impedance calculated at the voltage of the meshed node.

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$$V_S = (Z_C + Z_{line1} + Z_l) \times i_{l1} + (Z_l + Z_C) \times i_{l2}$$
$$V_S = (Z_C + Z_l) \times i_{l1} + (Z_l + Z_C + Z_{line2}) \times i_{l2} \quad (2)$$

In the above, two equations have been written for the *i*, and to apply the radial network solution algorithm meshed node *i* had been represented by i_1, and i_2. Thus, the voltage of node *i* = the voltage of i_1 = the voltage of the original meshed node $i = Z_l(i_{l1} + i_{l2})$.

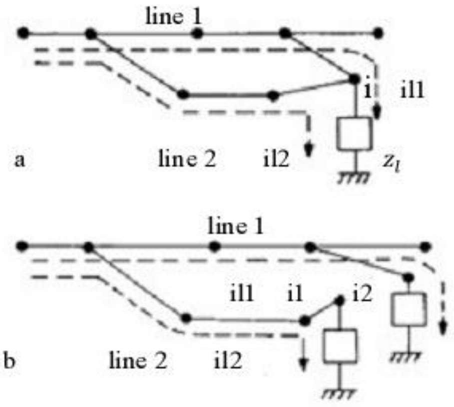

Fig. 1. (a) meshed node, (b) after breaking node to two

III. STEP VOLTAGE REGULATOR

A step-voltage regulator consists of an autotransformer and a load tap changing mechanism. The voltage change is obtained by changing the taps of the series winding of the autotransformer. The position of the tap is determined by a control circuit (line drop compensator).An autotransformer is constructed by utilizing a two-winding transformer and connecting the two windings in series as shown in Fig 2. In this figure, the non-polarity connection from one winding is connected to the polarity connection on the second winding. In this situation the resulting input voltage, VH, is larger in magnitude than the resulting output voltage, VI. The resulting winding ratio for the autotransformer is (N2 +Nl)/Nl. This situation would represent the extreme buck position on a standard single- phase voltage regulator, due to the fact that the load voltage is lower than the source voltage. Since the transformer is still a two winding unit, the ampere-turns must balance on the core, resulting in the current relationships shown. In the autotransformer connection most of the current passes through the series, or top part of the winding, while the shunt or bottom part of the winding carries a small current.

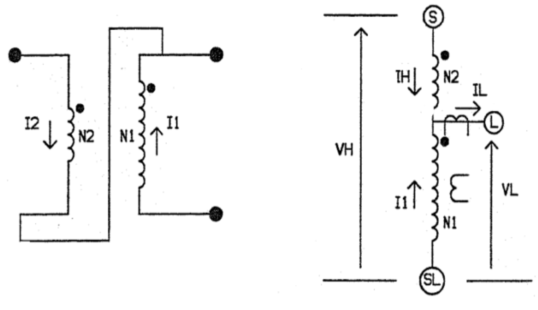

Fig. 2. Decreasing (bucking) autotransformer

Fig. 2 also displays some labels on the connections of the regulator. The three terminals are labeled "S" for source, "SL" for source-load and “L for load. The secondary winding positions for the current transformer and potential winding are also shown. They positioned to monitor the voltage and current applied to and flowing through the load, respectively. Depending on the connection of the regulator, the current reported by the CT may or may not be a direct transformation of the actual load current. The voltage is always intended to be the output voltage presented to the load The CT and PT secondary outputs are, however, used by the control in all situations. The configuration shown is known as the type B regulator connection. The regulator may also connect the windings in such a way that output, or load voltage is higher than the voltage from the source. This "boost" connection is shown in Fig. 3 In order to boost voltage, the connection must result in the direct connection of the polarity end of one winding to the polarity end of the second winding. In order to maintain ampere-turn balance on the core of the transformer, the current flowing in the shunt winding must reverse direction. For this reason the arrow is reversed when compared to Fig. 2. The voltage transformation equations remain the same yet result in a multiplier that is less than one. Thus the source side voltage VH is lower than the load voltage VL relationships change slightly due to the polarity reversal in the shunt winding. Current and voltage equations for the type B regulator in raise and lower positions are shown in Table II respectively.

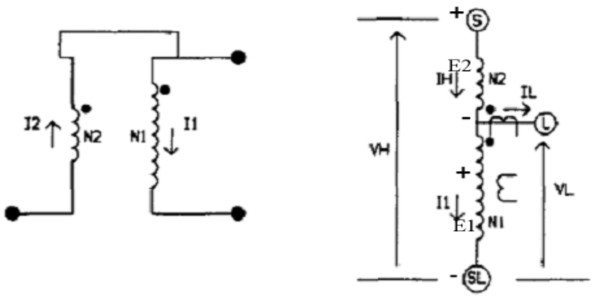

Fig. 3. Increasing (boosting) autotransformer

TABLE II: VOLTAGES AND CURRENTS EQUATIONS IN B TYPE REGULATOR

raise position		lower position	
$a_R = 1 - \frac{N_2}{N_1}$		$a_R = 1 + \frac{N_2}{N_1}$	
$\frac{E_1}{N_1} = \frac{E_2}{N_2}$	$N_2 I_H = N_1 I_L$	$\frac{E_1}{N_1} = \frac{E_2}{N_2}$	$N_2 I_H = N_1 I_L$
$V_S = E_1 + E_2$	$I_S = I_H$	$V_S = E_1 - E_2$	$I_S = I_H$
$V_L = E_1$	$I_L = I_S - I_1$	$V_L = E_1$	$I_L = I_S + I_1$
$E_2 = \frac{N_2}{N_1} E_1 = \frac{N_2}{N_1} V_L$	$I_1 = \frac{N_2}{N_1} I_2 = \frac{N_2}{N_1} I_S$	$E_2 = \frac{N_2}{N_1} E_1 = \frac{N_2}{N_1} V_L$	$I_1 = \frac{N_2}{N_1} I_2 = \frac{N_2}{N_1} I_S$
$V_S = (1 - \frac{N_2}{N1}) V_L$	$I_L = (1 - \frac{N_2}{N1}) I_S$	$V_S = (1 + \frac{N_2}{N1}) V_L$	$I_L = (1 + \frac{N_2}{N1}) I_S$
$V_S = a_R V_L$	$I_L = a_R I_S$	$V_S = a_R V_L$	$I_L = a_R I_S$

Standard step regulators contain a reversing switch enabling a ±10% regulator range, usually in 32 steps. This amounts to a 5/8% change per step, or 0.75 Volt change per step, on a 120-V base. The block diagram circuits shown in Fig. 4 controls tap changing on a step-voltage regulator. The step voltage regulator control circuit requires the following settings:

1) Voltage Level: the desired voltage (on a 120-V base) to be held at the load center. The load center may be the output terminal of the regulator or a remote node on the feeder.
2) Bandwidth: the allowed variance of the load center voltage from the set voltage level. The voltage held at the load center will be ± one half the band widths. For example, if the voltage level is set to 122 V and the bandwidth is set to 2 V, the regulator will change taps until the load center voltage lies between 121 and 123V.
3) Time Delay: length of time that a raise or lower operation is called for before the actual execution of the command. This prevents taps changing during a transient or short time change in current.
4) Line Drop Compensator: set to compensate for the voltage drop (line drop) between the regulator and the load center. The settings consist of R and X settings in volts corresponding to the equivalent impedance between the regulator and the load center. This setting may be zero if the regulator output terminals are the load center.

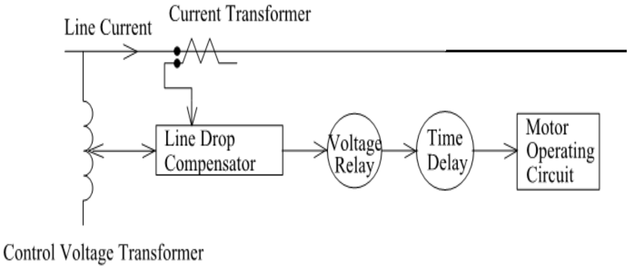

Fig. 4. Step voltage regulator control circuit

IV. STEP VOLTAGE REGULATOR MODEL

A. Single-Phase Step-Voltage Regulators

Because the series impedance and shunt admittance values of step-voltage regulators are so small, they will be neglected in the following equivalent circuits. It should be pointed out, however, that if it is desired to include the impedance and admittance, they can be incorporated into the following equivalent circuits in the same way they were originally modeled in the autotransformer equivalent circuit.

The actual number of turns on the series and shunt windings is not known, however, each change in tap changes the voltage by 5/8% or 0.00626 per unit. Therefore the effective regulator ratio can be given by:

$$a_R = 1 \pm \frac{N_2}{N_1} = 1 \pm 0.00625 Tap$$
$$V_L = \frac{1}{a_R} V_S$$
$$I_L = a_R I_S \qquad (3)$$

B. Three-Phase Step-Voltage Regulators

We can model the three-phase step-voltage regulators with Fig. 5.

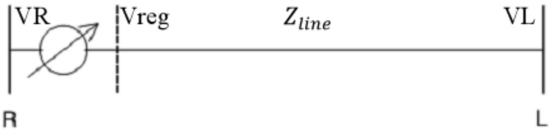

Fig. 5. Three-Phase Step-Voltage Regulator model

$$\left[V_{reg_{abc}}\right] = \left[A_L\right].\left[V_{L_{ABC}}\right]$$
$$\left[I_{abc}\right] = \left[D_L\right].\left[I_{ABC}\right] \qquad (4)$$

These regulators divide to five types:

1) Single-phase;
2) Two regulators connected in open wye;
3) Three regulators connected in grounded wye;
4) Two regulators connected in open delta;
5) Three regulators connected in closed delta.

You can see Wye-Connected Regulator in fig 6 and it equations are the following:

$$\begin{bmatrix} V_{AN} \\ V_{BN} \\ V_{CN} \end{bmatrix} = \begin{bmatrix} a_{Ra} & 0 & 0 \\ 0 & a_{Rb} & 0 \\ 0 & 0 & a_{Rc} \end{bmatrix} . \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} \qquad (5)$$

$$\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = \begin{bmatrix} 1/a_{Ra} & 0 & 0 \\ 0 & 1/a_{Rb} & 0 \\ 0 & 0 & 1/a_{Rc} \end{bmatrix} . \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \qquad (6)$$

In Equations (5) and (6), the effective turn's ratio for each regulator must satisfy:

0.9 < a < 1.1 in 32 steps of 0.625%/step (0.75 V/step on 120-V base) The effective turn ratios (a_{Ra}, a_{Rb}, a_{Rc}) can take on different values when three single-phase regulators are connected in wye.

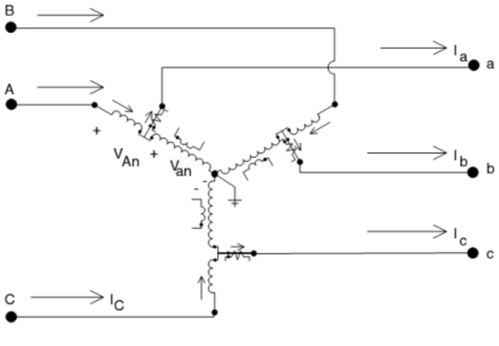

Fig. 6. Wye-connected type B regulators

It is also possible to have a three-phase regulator connected in wye where the voltage and current are sampled on only one phase, and then all three phases are changed by the same number of taps.

Two Type B single-phase regulators can be connected in the open delta connection. Shown in Fig 7 is an open delta connection where two single-phase regulators have been connected between phases CA and BA (in other papers AB and CB form pointed). Two additional open connections can be made by connecting the single-phase regulators between phases BC and AC, and also between phases AB and CB. The open delta-connected regulators will maintain only two of the line-to-line voltages at the load center within defined limits. The third line-to-line voltage will be dictated by the other two (Kirchhoff's voltage law). Therefore, it is possible that the third voltage may not be within the defined limits.

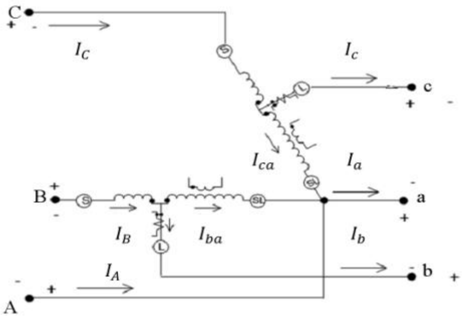

Fig. 7. Open delta connection

The closed delta connection can be difficult to apply. Note that in both the voltage and current equations, a change of the tap position in one regulator will affect voltages and currents in two other phases. As a result, increasing the tap in one regulator will affect the tap position of the second regulator. Therefore, in most cases the bandwidth setting for the closed delta connection will have to be wider than that for wye-connected regulators. In Fig. 8 you can see this model.

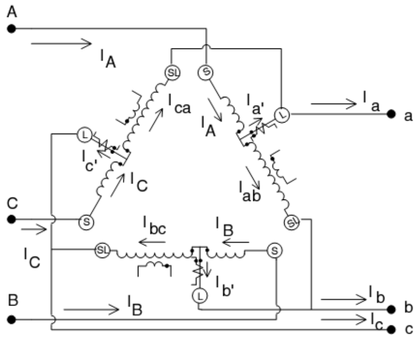

Fig. 8. Closed delta-connected regulators

C. Relation between Phase and Line in Delta Connected Regulators

The voltage transformers In delta regulators are monitoring the load side line-to-line voltages but in must load flow programs phase to natural voltages are calculated therefore for use of this model of voltage regulator must change $V_{ph\text{-}n}$ to $V_{L\text{-}L}$ and reverse.

V. TEST AND RESULTS

The one-line-diagram of the IEEE 34 Node Test Feeder [4] is shown in Fig. 9. This test feeder is based upon an actual feeder in rural Arizona. The original test feeder has two voltage regulators. For modify it we consider all loads in Y connection and connect 822 node to 848 node and 826 to 858 to change it to radial-meshed network. With algorithm of [3] determine the number of regulators and possible locations along with their settings. We name the nodes with 1-34 numbers that you can see in Table III.

In Fig. 10 voltage profile of radial system is shown and in Fig. 11 voltage profile of radial-meshed system. It is evident in radial-meshed voltages are in higher level. Reference voltage is 1.05 p. u with an angle of zero Degrees. First place a Y connected regulator in node 800 and adjusted to hold 126 volts output (according to ANSI standards maximum service voltage is 126 volt) and the load-flow program is run.

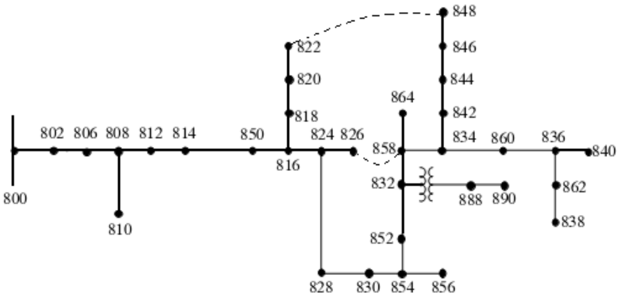

Fig. 9. Modified IEEE 34 node test feeder

TABLE III: FICTITIOUS NAMES OF NODES

Previous name	Next name	Previous name	Next name
800	1	856	18
802	2	852	19
806	3	832	20
808	4	888	21
810	5	890	22
812	6	858	23
814	7	864	24
850	8	834	25
816	9	842	26
818	10	844	27
820	11	846	28
822	12	848	29
824	13	860	30
826	14	836	31
828	15	840	32
830	16	862	33
854	17	838	34

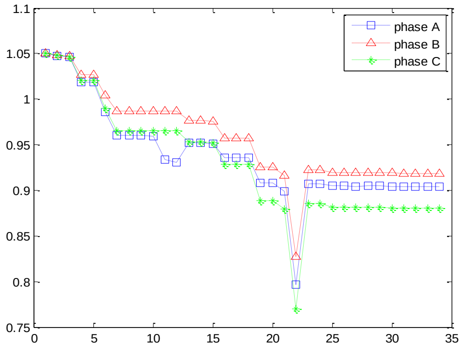

Fig. 10. Voltage profile of radial system

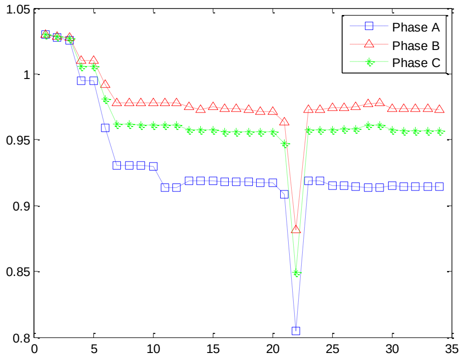

Fig. 11. Voltage profile of radial-meshed system

The location of the first downstream node that has a voltage below 120 volts is determined. For this case the voltages at node 812 are 113.3, 119.4 and 117.3 volts. To find the next node again put a Y connected regulator in node 812 and do previous tasks. The result of the load-flow study shows that all of the downstream voltages are equal to or greater than 120 volts. The only exception is node 890 which is at the end of a long 4.16 kV line. The voltages at 890 are 104.5, 107.8 and 105.7. For this case the only problem now are the voltages at node 890. This Node Voltages node is at the end of a 2 mile long 4.16 kV line. The only way to fix the voltages is to install a regulator at the output of the step down transformer between nodes 832-888. In natural IEEE 34 Node Test Feeder we need the other voltage regulator in node 852 but in this because of two rings this regulator is eliminated. Finally we put these regulators in nodes 812 and 888, and then adjust them at 120,122. The final voltage profile is in Fig. 12.

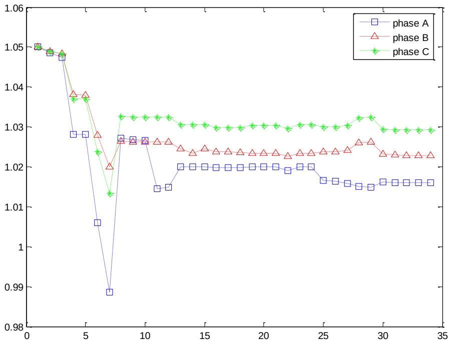

Fig. 12. Voltage profile of radial-meshed system with voltage regulators

VI. CONCLUSION

In this paper show the effect of mesh in reduce voltage regulators and how we find the place of voltage regulators. Results show the importance of using these equipments in distribution systems since they represent an economic alternative to improve network voltage profiles.

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