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Improvement of Voltage Regulation in Distribution Network Equipped With OLTC Transformers and DG Units

M. Ajodani , M. Joorabian

Abstract**-- This paper analyzes the possibility of an under-voltage caused by installing a DG (Distributed Generation) unit on a feeder where voltage regulation is controlled by the substation OLTC (On Load Tap Changing) transformer that is equipped with LDC (Line Drop Compensator) controls. In this a case, the introduction of the DG may confuse the regulator in setting a lower substation transformer secondary voltage than necessary, thus causing excessively low voltages towards the feeder end. The section that follows derives approximate voltage drops along uniformly distributed feeders under the presence of a single DG unit. in this paper a method for maximum DG size at a given location, and minimum distance from the substation a given DG size can be installed, that result in acceptable voltage are derived. The proposed method is tested on distribution system, IEEE 11 node with slightly modified parameters. The results demonstrate the validity of the proposed method for impact of DG on voltage regulation feeders equipped with OLTC transformer.**

Index Terms— Distributed Generation (DG), Line Drop Compensator (LDC), On Load Tap Changing (OLTC), Voltage Regulation.

I. Introduction

The use of DG can cause the voltage to deviate above or below the permissible rang in some parts of feeder, thus resulting in the opposite effect of voltage support, unless careful coordination between DG and Voltage Regulation controller is carefully engineered [5]-[11].This paper analyzes the possibility of an under-voltage caused by installing a DG unit on a feeder where voltage regulation is controlled by with Substation OLTC transformer that equipped with LDC controls. In this a case, the introduction of the DG may confuse the regulator in setting a lower substation transformer secondary voltage than necessary, thus causing excessively low voltages towards the feeder end. The section that follows derives approximate voltage drops along uniformly distributed feeders under the presence of a single DG unit [2]-[3]. Simple expressions of maximum DG size at a given Location, and
Minimum distance from the substation a given DG size can be installed, that result in acceptable voltage are derived.

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The proposed method is tested with an actual circuit with slightly modified parameters in section IV .to simplify the analysis DG is considered to operate at unity power factor, a common practice for inverter-based DG systems, but the analysis can be expanded to include distributed generators that either generate or absorb reactive power without much difficulty.

II. Voltage Profile on Feeders Equiped with OLTC Transformer

As it is shown in Figure.1, a distribution feeder of length "*l*" with a uniformly distributed load is considered, where voltage regulation is controlled with the substation OLTC transformer with LDC. The resulting voltage profiles along the feeder at full load and half load are also shown in the "Figure. 1(b)". As the load varies, the regulator adjusts the transformer tap position such that the voltage at the "regulating point" along the feeder is kept constant [1]-[6]-[10]. The active and reactive power flow drop is also can be extracted:

$$u_d = u_0\left(1-\frac{d}{l}\right),\dots\dots\dots\ .(u = P, Q) \quad (1)$$

$$P_d = P_S\left(1-\frac{d}{l}\right),\ Q_d = Q_S\left(1-\frac{d}{l}\right) \quad (2)$$

Where P_S and Q_S are the MW and MVAR flow at the substation end of the feeder, and "*l*" is the total length of the line as illustrated in "Figure.2" the per-unit (P-U) value of the total voltage drop across the feeder can be approximated by [8]-[9]:

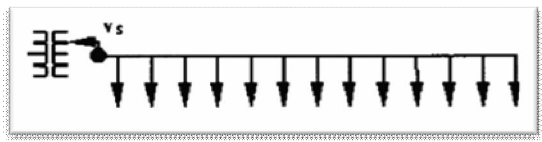

Fig. 1(a): distribution feeder of length *l* with a uniformly distributed load

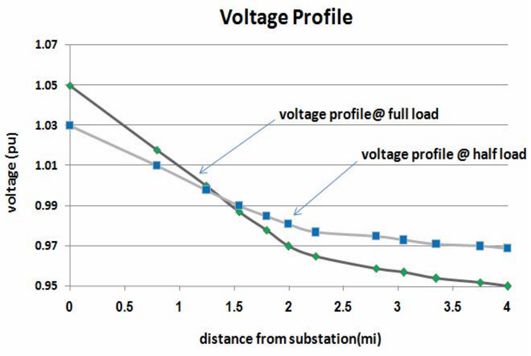

Fig. 1(b): Voltage Regulation by OLTC Transformer with LDC

$$VD_d = \frac{l(RP_S + XQ_S)}{2V_b^2} \quad (3)$$

Where V_b is the normal line-to-line voltage (KV), and "R" and "X" represent the feeder equivalent resistance and inductive reactance in Ohms per mile. The above voltage drop will be altered when a DG is installed on the feeder, and its deviation depends on both the DG size and location. P_G is the real power produced by a DG that is installed at some distance "d" from substation [4]-[5]. The modified expressions of the voltage drop are considered for two cases. These cases are shown below.

Case I (when $P_G < P_d$)

Case II (when $P_G > P_d$)

Are, derived next.

A. CASE I: $P_G < P_d$

When $P_G < P_d$, the voltage drop can be decomposed in two components as illustrated in "Figure.2(c)": the voltage drop between the substation and DG location, and voltage drop between the DG location and feeder end.

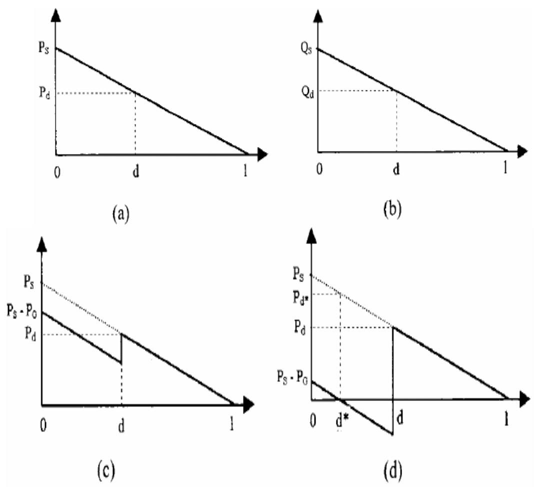

Fig.2: Active and Reactive power profile along feeder without DG at distance d from substation

Voltage drop between the "0" and "d":

$$VD_{0-d} = d\frac{R(P_d - P_G) + XQ_d}{V_b^2} + \frac{d}{2}\frac{(P_d - P_G) + X(Q_s - Q_d)}{V_b^2}$$

(4)

Voltage drop between "d" and "l":

$$VD_{d-l} = \frac{(l-d)}{2}\left(\frac{RP_d + XQ_d}{V_b^2}\right) \quad (5)$$

The total drop across the feeder is then approximated by:

$$VD = VD_{0-d} + VD_{d-l} \approx \frac{l(RP_S + XQ_S) - 2dRP_G}{2V_b^2} \quad (6)$$

B. CASE II: $P_G < P_d$

This case is illustrated in "Figure .2(d)" where power flow reversal exists. This causes the so-called "zero point" denoted by "d*" in the graph, where active power flows "uphill" towards the substation to the right of the zero point, and "downhill" in a conventional way to the left of the zero point. It is clear from "Figure .2(d)" that the zero point is computed by;

$$d^* = \left(1 - \frac{P_G}{P_S}\right)l \quad (7)$$

In here, the voltage drop is computed across each line segments as follows:

Voltage drop between "0" and "d*":

$$VD_{0-d*} = \frac{d*}{2}\frac{R(P_S - P_G) + X(Q_S - Q_{d*})}{V_b^2} \quad (8)$$

Voltage drop between "d*" and "d":

$$VD_{d*-d} = \frac{(d - d*)}{2}\frac{R(P_d - P_G) + X(Q_d - Q_{d*})}{V_b^2} \quad (9)$$

Where

$$Q_{d*} = Q_S\left(1 - \frac{d*}{l}\right) \quad (10)$$

Voltage drop between "d" and "l":

$$VD_{d-l} = \frac{(l-d)}{2}\left(\frac{RP_d + XQ_d}{V_b^2}\right) \quad (11)$$

The total voltage drop across the feeder can be obtained by summing the three voltage drops above:

$$VD = VD_{0-d*} + VD_{d*-d} + VD_{d-l}$$

$$\approx \frac{dR(XQ_{d*} - P_G) + (RP_S + XQ_S)\left\{l + d\left(\frac{d*}{l} - 1\right)\right\}}{2V_b^2} \quad (12)$$

III. CRITICAL FACTOR FOR DG SIZING AND SITING

Note that the voltage drop in "(12)" is both a linear function of the DG size P_G (i.e., VD=α. P_G +β) as well as location "*d*" (i.e., VD=λ. d +σ). Hence one can easily determine either a critical DG size of fixed location, or a critical location of a fixed DG size, that can result in maximum allowable voltage drop VD. The maximum allowable VD depends on the magnitude of the voltage V_S set by the OLTC with LDC at the substation end:

$$VD_{\max} = V_S - 0.95 \quad (13)$$

The magnitude of V_S at the substation can be approximated by a linear function of the power flow at the substation end:

$$V_S = 1 + 0.05\frac{P_S - P_G}{P_S} \quad (14)$$

Hence, for a given DG of size P_G , its minimum distance from the substation that does result in an under-voltage at the feeder end is computed by:

$$d_{\min} = \frac{1}{l}(V_s - s - 0.95) \quad (15)$$

Likewise, the maximum DG size located at a fixed location "d" that result in an acceptable voltage at the feeder end approximated by:

$$P_{G-\max} = \frac{P_{S(0.1-b)}}{a + 0.05} \quad (16)$$

IV. CASE STUDY

To illustrate the analyses presented earlier, an actual circuit with slightly modified parameters is studied in this paper. The circuit consists of a 30 MVA "138/20" kV OLTC transformer with 11% impedance that supplies a "4-mile" long distribution feeder (394 MCM cable with rated capacity of 600A). The resistance and inductive reactance ("GMD=5") of the line are".28 Ω/mi" and "0.64Ω/mi", respectively. A schematic of this feeder is shown in "Figure.3", and its section lengths and installed peak load at each of the 11 nodes are listed in "Table I". Note that the total peak load is (p_0, Q_0)= (10MW, 5MVAR).

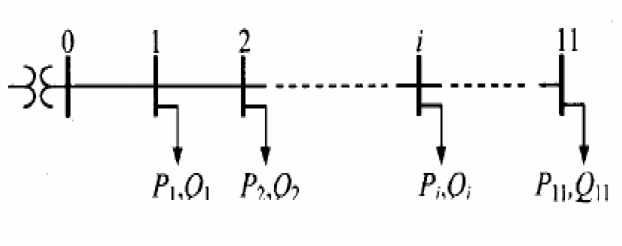

Fig.3: Radial Distribution Network.

In the case study the OLTC of the substation transformer is assumed to adjust the secondary voltage to 1.05 at peak load, and down to 1 at no load in linear fashion.

A. *Impact of DG on voltage regulation with OLTC transformer action.*

To check the accuracy of the approximate expressions derived in sections II and III, the example circuit with uniformly distributed load model is revisited in this section.

According to the analysis in [10] the error between the uniformly distributed load model and concentrated load model is within 1%, hence only the uniform load is considered here.

The OLTC transformer is assumed to adjust the secondary voltage to 1.05 PU at peak load, and down to 1 PU at no load in linear fashion. Prior to DG installation, the voltage profile along the feeder is shown in "Figure.4" for four load levels, i.e., 100%,75%,50% and 25% of peak load.

The LDC controls adjusts the OLTC transformer tap such that the feeder voltage at 1.6 mi from the substation is maintained at the normal value of 1 PU. The largest voltage drop of 8% occurs during peak load (as indicated by the blue-colored curve). The voltage drop calculated by "(3)" during peak load is 7.7%.

Hence, the approximations made are sufficiently accurate. "Figure.5" shows the new voltage profile after installing a 5MW distributed generator (or 50% DG penetration during peak load) at different locations along the feeder. The voltage profile curve prior to DG installation is also shown in "Figure.5" for reference purposes. When this particular DG is installed at the end of the feeder, it tends to raise the voltage from 0.927 P-U to 0.984 PU, thus providing voltage support.

On the other hand, when it is moved close to the substation, it causes the last mile of the feeder to operate at a voltage below 0.95 PU. This situation is often referred to as "the fooling of OLTC by DG" since it confuses the OLTC by setting a voltage lower than is required to maintain adequate service.

Table I: Feeder and Load Data

i	di-1,I (Mile)	Pi (MW)	Qi (MVAR)
1	0.80	2.1	1.3
2	0.45	1.4	0.8
3	0.30	1.0	0.6
4	0.25	0.5	0.1
5	0.20	0.8	0.2
6	0.25	0.6	0.3
7	0.55	0.9	0.5
8	0.25	1.3	0.6
9	0.30	0.3	0.1
10	0.40	0.5	0.2
11	0.25	0.6	0.3

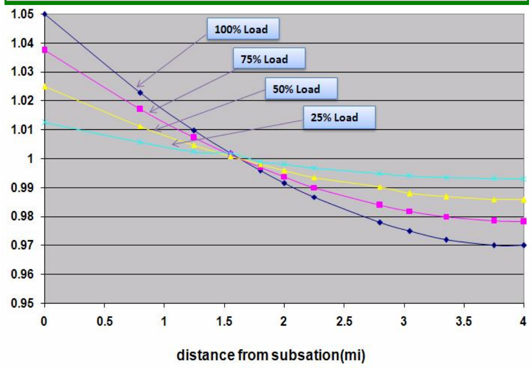

Fig. 4(a): feeder voltage profile at different load levels prior to DG installation

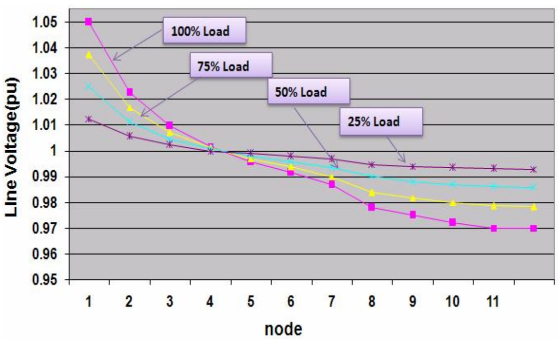

Fig. 4(b): feeder voltage profile at different load levels prior to DG installation

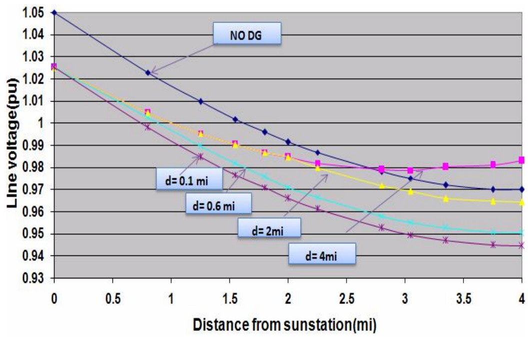

Fig. 5(a): voltage profile with 5 MW DG installed at different locations during peak load

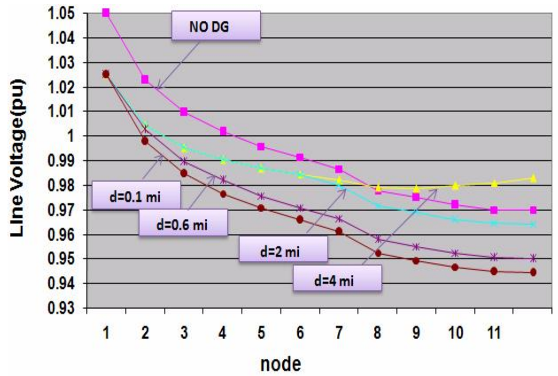

Fig. 5(b): voltage profile with 5 MW DG installed at different locations during peak load

The minimum distance $d_{\min}$ from the substation that a 5MW DG unit will result in acceptable voltage throughout the feeder is estimated to be 0.6 mi by "(15)". The green curve in "Figure.5" represents the corresponding voltage profile, and is in agreement since the voltage barely reaches the minimum allowed value at the feeder end. "Figure.6" shows the voltage profile for different DG sizes installed at a fixed point located 1 mi from the substation during peak load. The maximum DG size at this particular location that will not result in under-voltage at the feeder end estimated by "(16)" to be 6.4 MW. The corresponding voltage curve (green color (a)) verifies that such a limit is sufficiently accurate.

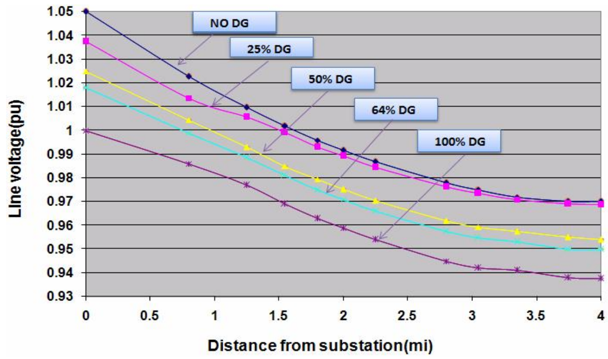

Fig. 6(a): voltage profile for different DG sizes installed at 1 mi from substation during peak load

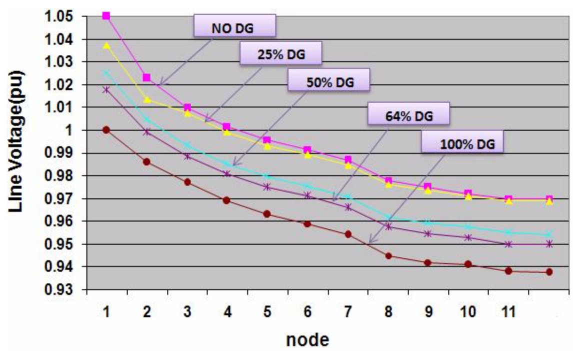

Fig. 6(b): voltage profile for different DG sizes installed at 1 mi from substation during peak load.

V. CONCLUSION

Installing distributed generation units along power distribution feeders may lead to over-voltage due to excessive active and reactive power injection. This paper illustrated the possibility of experiencing under-voltage towards the end of a distribution feeder (whose voltage is regulated by and OLTC transformer with LDC) when a DG of significant size is connected close to the substation end. In such a situation, the DG "fools" the Tap controls by making the feeder load appear to have a lighter load, thus reducing the substation voltage to a value lower than necessary. On the other hand, maintaining the substation voltage at the highest permissible value by disabling the LDC controls may result in over-voltage when a sufficiently large DG unit is installed towards the feeder end.

As a consequence, coordination between distributed generator output and OLTC transformer tap controls is necessary to avoid voltage regulation problems.

VI. APPENDIX

OLTC Transformer Data Compensating impedance:

Z_{eq} =0.075 + j0.039 [p. u]

Reference voltage:	V_{ce} =1.0 [p. u]
Total tap number:	K=17 [steps]
Time delay:	dt =120 [sec]
Dead band:	db = 0.0125 [p. u]

VII. REFERENCES

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BIOGRAPHIES

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