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A novel tuning method for advanced line drop compensator and its application to response coordination of distributed generation with voltage regulating devices

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Abstract

Nowadays, integration of small-scale electricity generators, known as Distributed Generation (DG), into distribution networks has become increasingly popular. This tendency together with the falling price of DG units has a great potential in giving the DG a better chance to participate in voltage regulation process, in parallel with other regulating devices already available in the distribution systems. The voltage control issue turns out to be a very challenging problem for distribution engineers, since existing control coordination schemes need to be reconsidered to take into account the DG operation. In this paper, a control coordination approach is proposed, which is able to utilize the ability of the DG as a voltage regulator, and at the same time minimize the interaction of DG with another DG or other active devices, such as On-load Tap Changing Transformer (OLTC). The proposed technique has been developed based on the concepts of protection principles (magnitude grading and time grading) for response coordination of DG and other regulating devices and uses Advanced Line Drop Compensators (ALDCs) for implementation. A distribution feeder with tap changing transformer and DG units has been extracted from a practical system to test the proposed control technique. The results show that the proposed method provides an effective solution for coordination of DG with another DG or voltage regulating devices and the integration of protection principles has considerably reduced the control interaction to achieve the desired voltage correction.

Keywords

distributed, coordination, response, application, its, compensator, drop, line, generation, advanced, devices, method, tuning, novel, voltage, regulating

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A Novel Tuning Method for Advanced Line Drop Compensator and its Application to Response Coordination of Distributed Generation with Voltage Regulating Devices

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Abstract -- Nowadays, integration of small-scale electricity generators, known as Distributed Generation (DG), into distribution networks has become increasingly popular. This tendency together with the falling price of DG units has a great potential in giving the DG a better chance to participate in voltage regulation process, in parallel with other regulating devices already available in the distribution systems. The voltage control issue turns out to be a very challenging problem for distribution engineers, since existing control coordination schemes need to be reconsidered to take into account the DG operation. In this paper, a new tuning method for line drop compensator has been proposed and it is applied for control coordination of DG with other regulating devices in the network, which is able to utilize the ability of the DG as a voltage regulator, and at the same time minimize the interaction of DG with another DG or other active devices, such as On-load Tap Changing Transformer (OLTC). The proposed coordination technique has been developed based on the concepts of protection principles (magnitude grading and time grading) for response coordination of OLTC, DG unit and other regulating devices. A distribution feeder with tap changing transformer and DG unit has been extracted from a practical system to test the proposed control technique. The results show that the proposed method provides an effective solution for coordination between OLTC and DG, DG-DG or DG and voltage regulating devices and the integration of protection principles has considerably reduced the control interaction to achieve the desired voltage correction.

Index Terms -- Distributed Generation, Voltage Control Design, Tap Changing Transformer, Line Drop Compensator.

I. INTRODUCTION

The increasing importance of reducing greenhouse gas emissions has been the key drive for a number of Australian government programs which aim to facilitate new generation projects with lower gas emissions than the pool average [1]. These generators are normally intended to operate whilst electrically connected to the distribution network, and utilize renewable energy (hydro, solar, wind, biomass) or low greenhouse emission fuels (natural gas). They are known as Distributed Generation (DG) resources. Not only the connection and operation of the DG can reduce environmental emissions, but it also offers a number of benefits compared to the conventional ones, such as lower capital cost of generation, generation capacity to more closely match the demand, as well as higher potential for enhanced security of supplies and improved power quality [2]. For these reasons, interest for installation of DG has been growing rapidly worldwide in the last decade.

At present, many DG units are of an induction-motor type, thus absorb reactive power from the grid, and synchronous type DG units that can inject real and reactive power into grid system, are very small in number. Therefore, DG units are not actively participating in the voltage regulation process. However, it is expected that in the near future, the combination of rapid load growth and falling price of DG technologies will trigger participation of a much greater number of synchronous generators into distribution systems. This tendency will in turn lead to the prospect of the supporting the main grid in maintaining acceptable voltage levels by DG units. The connection of DG plus the growth of load demand and the uncertainties of load connection/disconnection, nevertheless, have been contributing to the complexity of voltage regulation [3]. Traditional voltage control actions, in the absence of DG, depend much on the fact that the voltage profile decreases along the feeder from the substation to the remote end. In contrast, the integration of DG systems makes this characteristic no longer valid. Another possible difficulty involves the chance of introducing interaction among different control devices including DG units. As a result, the existing voltage control strategies need to be revised and redesigned [4].

Voltage control problem in the presence of DG has been addressed in the literature recently. Ma *et al* [5] have used the hierarchical genetic algorithm (HGA) to optimize the voltage control systems according to the number of control actions. In [6], an integrated voltage control called Coordinated Secondary Voltage Control (CSVC) has been proposed for controlling the OLTC to ensure that voltage and loading constraints are satisfied during normal and emergency conditions. Authors in [7] have developed a voltage regulation method in power distribution systems including DG systems through optimizing the sending end voltage using the Least Square method. Baldick and Wu [8] have developed a coordinated approach for the operation of switched capacitors and OLTC in a radial distribution system by approximating the problem as a constrained discrete quadratic optimization. In [9], a method for coordinating the operation of DG and step voltage regulator for improvement of distribution system voltage regulation has been presented. In [17], a coordination scheme is developed for coordination of a single DG with OLTC with an advanced LDC which is developed based on uniformly distributed load.

In this paper, a new tuning method for advanced line drop compensator is proposed and a coordinated approach for controlling the operation of OLTC and single DG or multiple DG, used as primary system voltage regulators, has also been developed based on the principles of magnitude grading and time grading of protection system. The magnitude and time grading principles of protection system have been adapted in the proposed method to avoid the interaction between OLTC and DG or a DG with another DG, as well as to utilize effectively the capacity of OLTC and DG. Simulations have been carried out on a distribution feeder with consideration of time varying loads to examine its performance.

II. ADVANCED LDC FOR VOLTAGE PREDICTION

Normally, the control of Tap Changer and DG is implemented through controlling their local voltage at the point of common coupling. However, setting voltage references for these regulators is a very complicated task due to unpredictable load dynamics and high diversity in customers' locations. A low setting for the reference value might not achieve the required voltage condition of the customers. High setting, on the other hand, may lead to excessive operation of the regulating devices. Unnecessary actions of the OLTC or regulators as well as DG are undesirable because of economic reasons. Changing tap position of the OLTC causes transients and mechanical wear on itself, while DG overrunning results in expensive fuel cost and reduction of the machine's operational age. To overcome these challenges, the Line Drop Compensator (LDC) has been proved to be very promising. As LDC is more sensitive to the changes of load and system voltage, it is able to predict voltage drop more effectively. Therefore, it may help reduce the number of tap operation and DG running time. In addition, LDC can offer an accurate tuning process for voltage control. In this section, operating principles of the conventional LDC and the Advanced LDC have been discussed and a new tuning approach has been proposed.

The use of LDC is very common in both transmission and distribution systems. In practice, an LDC equipped with a modern regulating device normally predicts the voltage at a remote load center. The information of customers' voltage status provided by the LDC, in turn, will drive the operation of the corresponding regulator in an attempt to maintain this voltage within satisfactory limits. In principle, voltage at the load center is predicted by estimating the voltage drop and then subtracting it from the local voltage measurement at the regulating point. Basically, voltage prediction by a conventional LDC depends on the local measurements of voltage and current, as well as its internal parameter settings, such as *R* and *X*. These values are used to estimate voltage at the remote load with acceptable discrepancy, as indicated in following equation:

$$V_{pr}^{CLDC} = V_d - I_d\left(R + jX\right) \tag{1}$$

where, V_d and I_d are the local voltage and current measurements, and *R* and *X* are the parameters that represent resistance and reactance, respectively.

Design of *R* and *X* has been extensively discussed in [10-12]. The most common and simple way for tuning the R and X parameters is to put the LDC online and adjust the R and X until the prediction from the LDC provides relatively precise result. Those values will be kept constant until another tuning process is required to enhance the accuracy of the prediction. To make it possible for the LDC to give an indication of the remote voltage, the settings of R and X usually reflect the equivalent resistance and reactance and can be represented as:

$$R + jX = \alpha\left(R_{The} + jX_{The}\right) \tag{2}$$

where, R_{The} and X_{The} are the equivalent resistance and reactance of the system respectively, and α is the tuning factor of the conventional LDC.

As can be seen from the above, the accuracy of the conventional LDC depends greatly on the selection of *R* and *X*. Bad choices of those parameters will cause imprecise prediction of the LDC. Also, operation of the tap changing and the DG systems inclusion have made the process of selecting *R* and *X* even more complicated [13]. In an earlier work of the authors [17], an advanced LDC is proposed that allows the estimation of the remote end voltage without any difficulties of choosing the LDC's internal coefficient settings. The voltage prediction by Advanced LDC is performed by utilizing only the local voltage and current measurements. The LDC works based on the assumption that the load is roughly uniformly distributed along the feeder, and thus the line current drops almost linearly from the measurement point *d* to the end of the feeder. The estimated current *I(x)*, which is far from the substation at a distance *x* can be written in the algebraic form as:

$$I(x) = \frac{1}{d-L}\left[\left(I_d - I_r\right)x + \left(I_r d - I_d L\right)\right] \tag{3}$$

where, *d* is the distance from the substation to the regulation, *L* is the feeder length. I_d and I_r are the local measured current at *d* and the current drawn by the remote load, respectively. Note that the I_r at any instant can be estimated using off-line load data with time reference.

Voltage prediction at the load center is determined by subtracting the estimated voltage drop from the measured voltage at regulating point *d* as:

$$V_{pr}^{LDC} = V_d - \underbrace{\beta \int_{x=d}^{f} zI(x)dx}_{\text{Estimated voltage drop}} \tag{4}$$

where, *z* is the line impedance per unit length and β is the tuning factor of the advanced LDC, and *f* is the distance from the substation to the point of voltage monitoring. A tuning process can be applied to the advanced LDC. The LDC is put online and the constant β could be determined. The possibility of inadequate voltage prediction caused by poor design of LDC internal settings has been eliminated by the advanced LDC. Therefore, using this more accurate prediction with higher confidence can be expected. The limitation of this method is that it does not provide good results in case there are substantial differences in the energy consumptions by the loads and in the distance between customers.

In this paper, a new tuning method for advanced line drop compensator is developed based on load position and energy consumption, which is the most sophisticated one, out of the three tuning approaches. It is expected to provide the most accurate results. This method requires some basic knowledge of the customers' loads, including the location and average energy consumption of each customer, which is available and easy to access. The procedure to estimate voltage at the remote end is described as follows:

a. Build up the admittance matrix with information of line and average load.
b. Calculate the remote voltage and current flow at the

regulating point (I_f) with respect to different ratios of actual load to the average load.

c. Develop a two-dimension table which expresses the relationship between remote voltage and the current I_f. By simulation, this relationship is very close to linear, thus they are assumed to be approximately linear.

d. The LDC measures the voltage and current at the regulating point. A linear search is then carried out using the local measurements and the table in Step (c) to determine the remote voltage.

Alternatively, we could use the numerical solution to define the relationship between I_f and V_r (remote voltage). Assume a network consists of n number of physical load buses. The network equation for the system is $[\mathbf{Y_{bus}}]\times[\mathbf{V_{bus}}]=[\mathbf{I_{bus}}]$. By expanding the network equation, we obtain:

$$\left[\begin{bmatrix}\mathbf{Y_a} & \mathbf{Y_b}\\ \mathbf{Y_b'} & \mathbf{Y_c}\end{bmatrix}+\alpha\begin{bmatrix}\mathbf{Y_1} & \mathbf{Y_2}\\ \mathbf{Y_2'} & \mathbf{Y_3}\end{bmatrix}\right]\begin{bmatrix}V_S\\ \mathbf{V_X}\end{bmatrix}=\begin{bmatrix}I_S\\ \mathbf{0}\end{bmatrix} \quad (5)$$

where, $\begin{bmatrix}\mathbf{Y_a} & \mathbf{Y_b}\\ \mathbf{Y_b'} & \mathbf{Y_c}\end{bmatrix}$ and $\begin{bmatrix}\mathbf{Y_1} & \mathbf{Y_2}\\ \mathbf{Y_2'} & \mathbf{Y_3}\end{bmatrix}$ are the line admittance matrix and the average load admittance matrix, respectively. Note that the load admittance matrix only has diagonal elements, thus $\mathbf{Y_2}$ = 0; V_S and I_S are the source voltage and current, respectively; the remaining bus voltage $\mathbf{V_X}$ = [V_2 … V_n]; and α is the load factor which is the ratio of the real load to average load.

From Eq. (5), we have:

$$(\mathbf{Y_c}+\alpha\mathbf{Y_3})\mathbf{V_X}=-\mathbf{Y_b'}V_S \quad (6)$$

By taking the derivative of Eq. (6) with respect to α and rearranging it, we get:

$$\frac{\partial\mathbf{V_X}}{\partial\alpha}=-(\mathbf{Y_c}+\alpha\mathbf{Y_3})^{-1}\mathbf{Y_3}\mathbf{V_X} \quad (7)$$

From simulation, we found that the voltage $\mathbf{V_X}$ is very close to a linear function of α. Thus, Eq. (7) could be simplified as,

$$\frac{\partial\mathbf{V_X}}{\partial\alpha}\approx-\mathbf{Y_c}^{-1}\mathbf{Y_3}\mathbf{V_X} \quad (8)$$

Voltage elements at bus 2 and n (or remote node at which voltage is V_r) could be extracted from Eq. (8) as follows:

$$\frac{\partial V_2}{\partial\alpha}\approx-e_2\mathbf{Y_c}^{-1}\mathbf{Y_3}\mathbf{V_X} \quad (9)$$

$$\frac{\partial V_r}{\partial\alpha}\approx-e_n\mathbf{Y_c}^{-1}\mathbf{Y_3}\mathbf{V_X} \quad (10)$$

For accuracy, we take the linearization of (9) and (10) around the mean load ($\alpha = \alpha_m$), and we obtain

$$V_2=V_{2,\alpha=\alpha_m}+\left.\frac{\partial V_2}{\partial\alpha}\right|_{\alpha=\alpha_m}\Delta\alpha=V_{2,\alpha=\alpha_m}-\left(e_2\mathbf{Y_c}^{-1}\mathbf{Y_3}\mathbf{V_X}\right)_{\alpha=\alpha_m}(\alpha-\alpha_m) \quad (11)$$

$$V_r=V_{r,\alpha=\alpha_m}+\left.\frac{\partial V_r}{\partial\alpha}\right|_{\alpha=\alpha_m}\Delta\alpha=V_{r,\alpha=\alpha_m}-\left(e_n\mathbf{Y_c}^{-1}\mathbf{Y_3}\mathbf{V_X}\right)_{\alpha=\alpha_m}(\alpha-\alpha_m) \quad (12)$$

This approach is applicable for any regulating position. For demonstration, we assume that regulating point is at the substation, which means $I_f = y_{1,2}\times(V_S - V_2)$, where y_{12} is the line admittance between the substation and load bus 2. Thus, we have:

$$I_f=y_{1,2}\left[V_S-V_{2,\alpha=\alpha_m}+\left(e_2\mathbf{Y_c}^{-1}\mathbf{Y_3}\mathbf{V_X}\right)_{\alpha=\alpha_m}(\alpha-\alpha_m)\right] \quad (13)$$

By rearranging Eq. (13) and substituting the function of α in term of I_f into Eq. (12), we obtain:

$$V_r=V_{r,\alpha=\alpha_m}-\left(e_n\mathbf{Y_c}^{-1}\mathbf{Y_3}\mathbf{V_X}\right)_{\alpha=\alpha_m}\left[\frac{I_f-y_{1,2}\left[V_S-V_{2,\alpha=\alpha_m}-\left(e_2\mathbf{Y_c}^{-1}\mathbf{Y_3}\mathbf{V_X}\right)_{\alpha=\alpha_m}\alpha_m\right]}{y_{1,2}\left(e_n\mathbf{Y_c}^{-1}\mathbf{Y_3}\mathbf{V_X}\right)_{\alpha=\alpha_m}}-\alpha_m\right] \quad (14)$$

III. A COORDINATED VOLTAGE CONTROL

In general, the voltage of a feeder is controlled by an OLTC transformer at the substation and one or more capacitor banks along the feeder. The transformer controls the secondary side voltage magnitude directly by changing its tap position, while the capacitor banks affect the higher side voltage magnitude indirectly by changing the amount of reactive power demand at the bus [14]. In this paper, not the capacitor banks but DG is used which is able to alter the voltage indirectly by changing the amount of both real and reactive power. Traditionally, the control of the OLTC is performed in a simple way with sensing the need to raise or lower the tap position, and correcting the voltage until a tap position limiting switch prevents further excursion of the tap changer [15]. Similar concept is adopted here to control the operation of OLTC and DG. However, for a better voltage control scheme, especially when there are more than one voltage regulating devices are employed, more advanced arrangement needs to be developed.

In this section, the mission of maintaining system voltage within the specified limits is achieved by controlling the tap position of the OLTC and the output current from a DG. Each of them is equipped by an Advanced LDC and they, both are responsible for improving the remote end voltage. Voltage at the remote load is chosen as the driven factor for the operations of OLTC and DG. The reason is that the remote end voltage of a radial feeder is usually low and it is the position where the worst voltage situation would most likely to occur. To improve the performance of the control system, a time delay and a voltage reference setting are integrated for each regulator. This is an imitation of the grading principles in protection system, which are known as time grading and magnitude grading as used in an earlier work of the authors [16]. The two grading schemes have been employed to assign a priority level for operation of each regulating device. Thus, the interaction between the regulating devices can be reduced or possibly eliminated. Moreover, another purpose of time grading is to avoid unnecessary control actions in response to temporary voltage drops. Such circumstances occur in real-time practice of voltage control due to short term load variations. However, they usually do not hold for long time and the system is expected to automatically recover. Thus, any response of tap changer or DG in those situations is undesirable by utilities. This problem is easily solved by inserting a time delay into the regulators. The first tap or first DG adjustment takes place only after a time delay, and then the consecutive responds will be faster. The delay is recommended to be long enough to overcome any unnecessary response.

The challenge of coordinating voltage regulating devices in the system without communication is that the chances of interaction between the units and instability of each unit itself are relatively higher compared to the communication case. To avoid these problems, settings of time delay and hysteresis band should be carefully selected to clearly distinguish the priority of each controller in a particular scenario. Selection of time delay has already been discussed in the previous work of the authors [17]. In the following subsections, the design of the hysteresis band and its implementation to coordination of a DG with OLTC will be presented.

A. Hysteresis Band Design for Coordinated Voltage Control

In order to avoid instability of the controller, particular attention must be paid to the criteria on which a DG needs to be turned ON or OFF. In other words, the DG should not be oscillating between ON and OFF status, for a given loading condition.

Let us assume that the voltage error at target bus 'j' is outside hysteresis band and the required current from DG, calculated by $K_P \Delta V_i$, is large enough:

$$\underbrace{K_P \Delta V_i}_{I_{DG}} \geq p_{ON} \tag{15}$$

where, K_P is the proportional controller, ΔV_i is the voltage error (noted that ΔV_i must be equal or larger than the hysteresis band of DG controller, *b*, for any DG action to take place), and p_{ON} is the minimum level of required DG current for the machine to switch ON.

The network equation can be partitioned into sub-matrices as follows, where Bus 1 represents the substation while bus *n* is the remote load bus of the feeder. The DG is represented by a current source connected to an additional bus, (*n+1*). Bus voltage and current of this system are related as [17]:

$$\begin{bmatrix} Y_1 & Y_2 & Y_4 \\ Y_2^T & Y_3 & Y_5 \\ Y_4^T & Y_5^T & Y_6 \end{bmatrix} \begin{bmatrix} V_{S-2} \\ V_{3-N} \\ V_{DG} \end{bmatrix} = \begin{bmatrix} I_{S-2} \\ 0 \\ I_{DG} \end{bmatrix} \tag{16}$$

where, $Y_1 = \begin{bmatrix} y_{1,1} & y_{1,2} \\ y_{2,1} & y_{2,2} \end{bmatrix}$, $Y_2 = \begin{bmatrix} y_{1,3} & \cdots & y_{1,n} \\ y_{2,3} & \cdots & y_{2,n} \end{bmatrix}$,

$Y_4 = \begin{bmatrix} y_{1,n+1} \\ y_{2,n+1} \end{bmatrix}$, $Y_3 = \begin{bmatrix} y_{3,3} & y_{3,4} & \cdots & y_{3,n} \\ \vdots & \vdots & \vdots & \vdots \\ y_{n,3} & y_{n,4} & \cdots & y_{n,n} \end{bmatrix}$,

$Y_5 = \begin{bmatrix} y_{3,n+1} \\ \vdots \\ y_{n,n+1} \end{bmatrix}$, $Y_6 = \left[y_{n+1,n+1} \right]$, $V_{3-N} = \begin{bmatrix} V_3 \\ \vdots \\ V_n \end{bmatrix}$,

$V_{S-2} = \begin{bmatrix} V_S \\ V_2 \end{bmatrix}$, $I_{S-2} = \begin{bmatrix} I_S \\ I_2 \end{bmatrix}$

V_S and I_S are the voltage and current at the substation. From (16), the changes of voltages in the system due to DG injecting current can be calculated as below:

$$\begin{bmatrix} Y_D & Y_E \\ Y_E^T & Y_F \end{bmatrix} \begin{bmatrix} \Delta V_{im} \\ \Delta V_i \end{bmatrix} = \begin{bmatrix} 0 \\ \Delta I \end{bmatrix} \tag{17}$$

where, $Y_D = \begin{bmatrix} Y_1 & Y_2 \\ Y_2^T & Y_3 \end{bmatrix}$ $\quad Y_E = \begin{bmatrix} Y_4 \\ Y_5 \end{bmatrix}$ $\quad Y_F = \left[Y_6 \right]$

$\Delta V_{im} = \begin{bmatrix} \Delta V_{S-2} \\ \Delta V_{3-N} \end{bmatrix}$ $\quad \Delta V_i = \left[\Delta V_{DG} \right]$ $\quad \Delta I = \left[\Delta I_{DG} \right]$

From (17), we get

$$\left\{ Y_F - Y_E^T Y_D^{-1} Y_E \right\} \Delta V_i = \Delta I \tag{18}$$

Rearranging (18), we obtain

$$\Delta V_i = \left\{ Y_F - Y_E^T Y_D^{-1} Y_E \right\}^{-1} \Delta I \tag{19}$$

From (17) and (19) and substituting $\Delta I = K_P \Delta V_i$, the improvement of voltage error in the system as the result of DG injecting current can be obtained as,

$$\mathbf{\Delta V}_{im} = -\mathbf{Y_D^{-1}} \mathbf{Y_E} \left(\mathbf{Y_F} - \mathbf{Y_E^T} \mathbf{Y_D^{-1}} \mathbf{Y_E} \right)^{-1} \left(K_P \Delta V_i \right) \tag{20}$$

Equation (20) is presented in the form of a vector from which voltage error improvement at a particular bus in the system can be extracted.

The required output from DG now becomes:

$$I'_{DG} = K_P \left[\Delta V_i + e_j \mathbf{Y_D^{-1}} \mathbf{Y_E} \left(\mathbf{Y_F} - \mathbf{Y_E^T} \mathbf{Y_D^{-1}} \mathbf{Y_E} \right)^{-1} \left(K_P \Delta V_i \right) \right] \tag{21}$$

where, $e_j \mathbf{Y_D^{-1}} \mathbf{Y_E} \left(\mathbf{Y_F} - \mathbf{Y_E^T} \mathbf{Y_D^{-1}} \mathbf{Y_E} \right)^{-1}$ is the vector element corresponding to target bus 'j'.

It is expected that the status of DG current, given by (21) is large enough for the DG to remain or maintain ON:

$$I'_{DG} \geq p_{OFF} \tag{22}$$

where, p_{OFF} is the maximum level of required DG current for the machine to switch OFF.

The introduction of p_{OFF} is to make sure that DG will not be running at a low output level, which is not an economic solution. From (19), (21) and (22), we obtain the condition of p_{ON} and p_{OFF} as,

$$\frac{p_{ON}}{p_{OFF}} \geq \chi \frac{1}{1 - e_j \mathbf{Y_D^{-1}} \mathbf{Y_E} \left(\mathbf{Y_F} - \mathbf{Y_E^T} \mathbf{Y_D^{-1}} \mathbf{Y_E} \right)^{-1} K_P} \tag{23}$$

The factor χ (with $\chi \geq 1$) has been included to keep a clear margin between two: p_{ON} and p_{OFF}. The bigger the factor is, the smaller the chance of DG controller's instability. The hysteresis band of DG for ON/OFF should be selected in such a way that the condition given by (23) is satisfied. From this, hysteresis band of the OLTC can also be chosen accordingly so that the operation of the OLTC is maximally utilized.

B. Coordination of a DG Unit with an OLTC

The actions of the OLTC can be classified into three types: do nothing, tap up, and tap down. These actions are coded as 0, +1, and -1, respectively. The following rules are used to control OLTC:

1) Default status of the OLTC is 0
2) If $V_{pr1} < V_{ref1}$ – dead band: current status is +1
3) If $V_{pr1} > V_{ref1}$ + dead band: current status is -1
4) Otherwise, current status is 0

where, V_{ref1} is the reference voltage and V_{pr1} is the estimated remote voltage of the OLTC controller. A counter is set up in the controller with default value of zero to make sure that tap change of OLTC is occurred for permanent voltage problems only. The control algorithm of the OLTC can be summarized as in the flow chart given in Figure 1.

The DG control strategy shares some similarities with the OLTC control algorithm. A variable called 'current status' mainly drives the decision making of the DG operation, and a 'counter' is engaged to trigger the action of the DG for actual need. Default values for both the 'current status' and the 'counter' are zero. Apparently, these variables perform their duties autonomously from those of the OLTC.

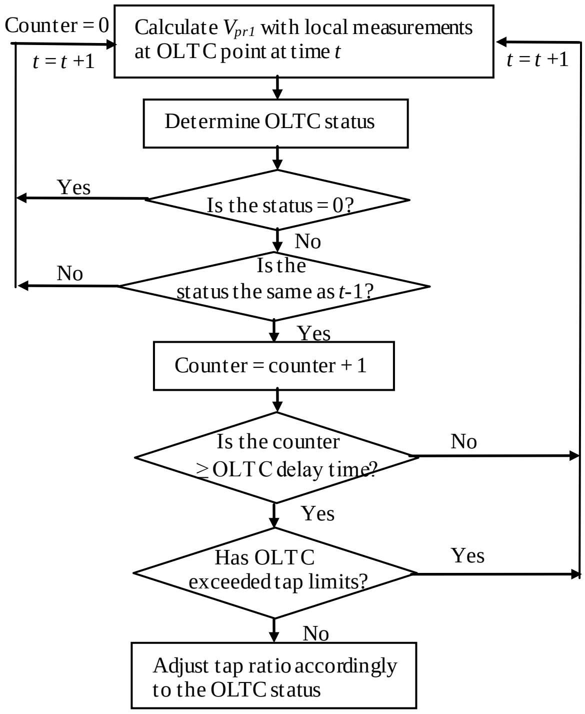

Figure 1: OLTC controller algorithm

Current status of the DG can be defined as below:

1) If $V_{pr2} < V_{ref2}$ – lower tolerance: current status is +1
2) If $V_{pr2} > V_{ref2}$ + upper tolerance: current status is -1
3) Otherwise, current status is 0

where, V_{ref2} is the reference voltage and V_{pr2} is the estimated remote voltage of the DG controller.

Lower tolerance is chosen in such a way that it is substantially smaller than the upper tolerance. The reason is that the DG reference voltage is generally set closer to the lower limit to satisfy the voltage requirement without over running or over loading the DG. The controller of proportional-integral (P-I) type can be used for the DG. Voltage error is derived based on the information provided by the advanced LDC with the addition of some level of tolerance and is used as the feedback signal for the controller. DG will adjust its output current to correct the voltage as,

$$\Delta|I_{DG}| = K_P\left(|V_{ref2}| - |V_{pr2}| + \varepsilon\right) \tag{24}$$

In this study, DG has been modelled as a constant current source and its phase angle is determined so as the DG would always give maximum voltage improvement in the feeder [10]. For economic reasons, it is assumed that DG is operated only if its output current is equal to or greater than a minimum value (e.g. 30% of the DG capacity). Otherwise, it will be switched off. The control logic of the DG is described in a step-by-step procedure as follows.

Step 1: Determine the current status of the DG at time t using the proposed advanced LDC and local measurements at DG connection point. If the status is +1 or -1, go to Step 2. Otherwise, go to Step 6.

Step 2: Does the status of the DG remain the same as that at time t-1? If yes, increase the counter by 1 and go to Step 3. If no, go to Step 6.

Step 3: Is the counter equal to or greater than the delay time of the DG? If yes, go to Step 4. If no, go to Step 7.

Step 4: Calculate the desired value of DG current output $|I_{DG}|$ by using Eq. (24). (For diesel or bio-diesel based DG, if the desired value is less than 30% of DG capacity, set $|I_{DG}| = 0$ to avoid low load operation due to economic reasons). If the desired value is more than 100% of DG capacity, set $|I_{DG}|$ = the maximum DG current. Otherwise, $|I_{DG}|$ is as given by the calculation. Go to Step 5.

Step 5: Adjust DG output as the desired value and go to Step 7.

Step 6: Reset counter to zero and go to Step 7.

Step 7: $t = t + 1$ and go to Step 1.

As mentioned earlier, the OLTC and the DG may experience interactions since both controllers are working towards the same aim of correcting the remote voltage [18]. These interactions, however, can be avoided by setting V_{ref1} significantly higher than V_{ref2}. The voltage reference level and delay time of the controllers were designed based on the concept of magnitude grading and time grading characteristics, respectively, of the protection system. The use of these principles helps to improve the performance of the control scheme in various ways, such as,

- OLTC and the DG controllers will only be activated in case of permanent voltage problems. Thus, mal-operation of controllers can be avoided;
- Utilized the capacity of the OLTC, which is considered as a less expensive method of voltage regulation. This will reduce the running cost of the DG; and
- Reduced the risk of interactions among the different controllers.

IV. A COORDINATED CONTROL APPROACH FOR COORDINATION OF OLTC AND DG SYSTEMS

For demonstration of the proposed control applicable to single DG and multiple DG, a single DG system and a two-DG system are used in this study. The voltage of the distribution network in this case is controlled simultaneously by an OLTC and a single DG or an OLTC and two DG units located at a certain distance apart from each other. Let us assume that DG1 is far away from DG2 which is located at the remote end. Two different voltage control schemes have been developed. One has no support from the communication system, while the other employs a minimum communication set-up. The following subsections have discussed the implementation of the proposed control scheme for OLTC and two DG systems without communication and with minimum communication. The application of the proposed scheme to coordinate OLTC and single DG system is very similar and simpler.

A. A COORDINATED CONTROL FOR OLTC AND DG WITHOUT COMMUNICATION

Although the proportional-integral (PI) controller with its fast response can give a good performance for voltage support, it may result in an unstable system. The higher the number of proportional-integral controllers in the system, the higher the chance of interaction among them. To reduce the risk of potential interaction and also reduce the possibility of controller instability, a non-communication control scheme is proposed that uses only the purely proportional controller (PC). The output of each DG in the system is controlled by a PC, which is driven by an Advanced LDC. Tap operation of the OLTC is determined by a feedback signal obtained from an Advanced LDC, which is attached to the tap changing transformer.

The implementation of control algorithms for the OLTC and the DG units is of interest. As more regulating devices are employed, hunting between regulating units is more likely to occur. To solve this problem, different targets, as defined below, have been assigned to different controllers given in Figure 2.

a) The OLTC regulates the remote voltage. Thus, feedback signal of the OLTC controller is the difference in magnitude between the voltage prediction of the remote end (predicted by the advanced LDC at tap point), and the reference voltage of the OLTC.
b) The DG1 regulates voltage at a load bus *k*, which is located in between DG1 and DG2. Thus, feedback signal of the DG1 controller is the difference in magnitude between voltage prediction of bus *k* (predicted by the advanced LDC at the DG1), and the reference voltage of the DG1.
c) The DG2 regulates the remote voltage. Thus, feedback signal of the DG2 controller is the difference in magnitude between the voltage prediction of the remote end (predicted by the advanced LDC at the DG2), and the reference voltage of the DG2.

Therefore, output signals of the two DG units can be determined as:

$$\left|I_{DGj}\right| = K_{Pj}\left(\left|V_{ref-DGj}\right| - \left|V_{pr-DGj}\right| + \varepsilon\right) \quad (25)$$

where K_{Pj} is the proportional constant of DG*j*; $V_{ref\text{-}DGj}$ and $V_{pr\text{-}DGj}$ are the reference voltage and estimated voltage, respectively, of the DG*j*, where j = 1, 2.

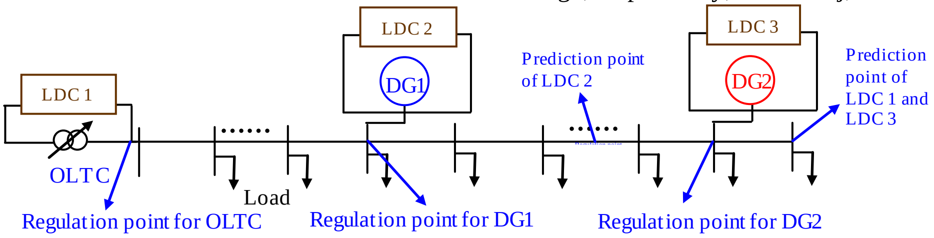

Figure 2: Targets of voltage regulation for non-communication control scheme

By applying these feedback signals to the controllers, the remote end voltage, which has the highest probability of voltage problem to occur, will be taken care by both the OLTC and the DG2. Moreover, the load bus with the next highest probability of voltage under specification is looked after by DG1. We assume that the second critical point is located between the DG1 and the DG2. This is due to the fact that since the current injections from the two generators result in voltage raises at the location of each DG, the midpoint (or a point near to this) between the DG units may suffer from low voltage condition. Moreover, in case if the DG2 is saturated or fails to work, the DG1 can act as the secondary voltage support equipment to the remote end voltage.

The magnitude grading and time grading principles of the protection system have also been adapted for this control scheme. The voltage reference of the OLTC controller is set to the highest to maximize the capability of the tap. The DG2 controller has the second highest voltage reference level, while the controller of the DG1 has the smallest reference. This is to ensure that the DG2, which is supposed to be more economical for voltage support, will have more chance to operate than the DG1. Also, different time delay settings are integrated for different controllers.

B. A Coordinated Control for OLTC and DG with Minimum Communication

In the availability of the communication system, we assume that there is a control center which is able to assign voltage correction level to each DG, according to their effectiveness. The OLTC, on the other hand, works independently from the group of the DGs. The communication set up proposed is bi-directional between the control center and the DGs, as shown in Figure 3. The control center basically has three main roles as discussed below:

a) Keeping track of voltage condition at the remote end by using the Advanced LDC.
b) Sharing the responsibility among the DGs depending on their efficiencies in regulating voltage at the remote end.
c) Transferring the regulating responsibility of one DG to another in case it is supposed to work under a certain limit (typically 20% of capacity by assumption) or fails to operate.

The controllers of the DG1 and DG2 in this control scheme are both proportional–integral (PI) type. As we have mentioned earlier, the PI controller in case of multiple DG system may lead to control instability. However, this problem can be solved by using a common integral part, which is controlled by the control center, of the two DGs. Thus, the DG outputs are determined as follows:

$$\Delta\left|I_{DGj}\right| = K_{Pj}\left(\left|V_{ref-C}\right| - \left|V_{pr-C}\right| + \varepsilon\right) \quad (26)$$

where K_{Pj} is the proportional constant of DG*j*. $V_{ref\text{-}C}$ and $V_{pr\text{-}C}$ are the reference voltage and estimated voltage, respectively, of the control center.

Moreover, it is more effective to locate the control center at the location of the DG2 or near to remote end. The reason of this is that the DG2, which is located closer to the remote end, is able to give more accurate voltage estimation as well as to correct the voltage more efficiently.

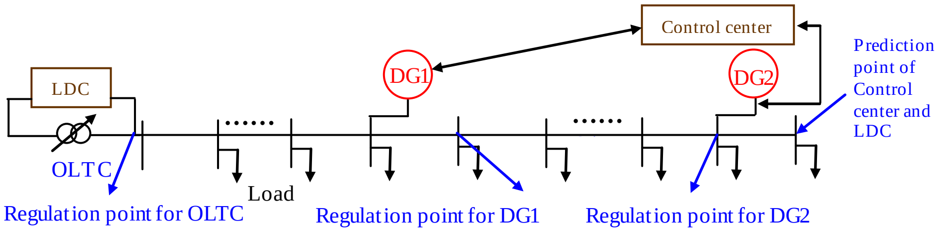

Figure 3: Targets of voltage regulation for minimum communication control scheme

V. RESULTS AND DISCUSSIONS

Tests were carried out on a test feeder extracted from a practical system for validating the proposed design of the Advanced Line Drop Compensator and also control strategy for coordination of OLTC and single DG or multiple DG systems. Results are reported in the following sub-sections.

A. TEST FEEDER WITH TIME VARYING LOAD DATA

An 11-kV distribution feeder (shown in Figure 4) of Aurora Energy, a distribution utility of Tasmania, Australia has been used for this study. The length of the main feeder is 48 km. As this feeder provides power to a low densely populated at rural area, even though it is considerably long, it does not have any backup substation and is thus a potential candidate of voltage support by DG. It has been modified to form a simplified test system shown in Figure 5 with 69 nodes.

The tap ratio (1 to '*a*') of the OLTC can be varied from *a* = 0.95 to *a* = 1.10. Each step is 1.25% and the delay time for the first tap is 4 seconds. In practice, an OLTC normally takes 30 seconds for the first tap movement. However, due to the short-time simulation, the time delay has been scaled down to 4 seconds. The LDC dead-band used in the OLTC is 1%. Each LDC that serves the DG has upper tolerance of 0.5% and lower tolerance of 0.2%.

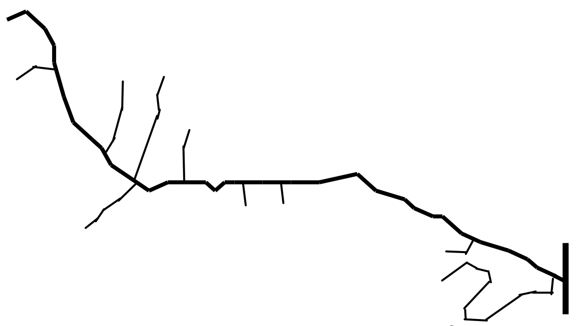

Figure 4: The Smithton - Woolnorth test feeder

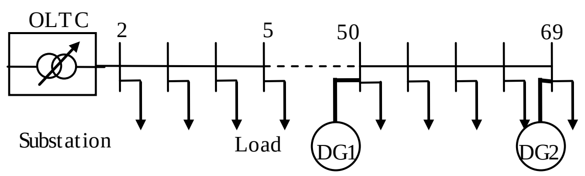

Figure 5: Diagram of a simplified test feeder

Simulations have been carried out for the duration of 200 seconds and 400 seconds with time step of one second to prove the usefulness of the proposed control. LDCs monitor their local voltage and current and periodically predict the regulating point voltages. If the estimated voltage is not considered to be safe within the acceptable limits, controller will be activated and control actions will be taken place immediately. The test system is designed to operate within ±5% from the nominal voltage.

A set of time-varying load data was generated for the test, by imitating the nature of load change, which is usually stochastic in time and magnitude. Total feeder load increases from 2.0 MVA to 4.3 MVA to demonstrate the transition from lightly loaded to heavily loaded conditions. To represent the stochastic nature of loads, the time-varying load data was generated based on the following characteristics:

(a) At time *t*, 20% of the load buses (selected randomly from the set of 68 buses) had their load levels varying compared to time *t-1*. Load variations were calculated by adding a certain amount of variation (randomly up to 2.5% of the prior load level) and a correction factor such that general increasing trend of load will be followed.

(b) The remaining 80% of customers maintained the same load as at time *t-1*.

(c) Real and reactive power variations were independent from each other, thus, customer power factor was not a constant value with respect to time.

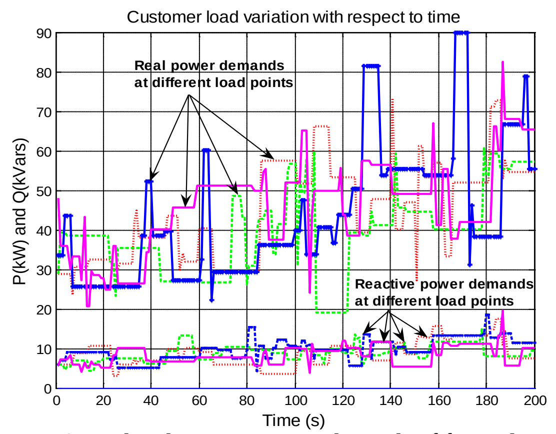

Figure 6: Real and reactive power demands of four selected customers

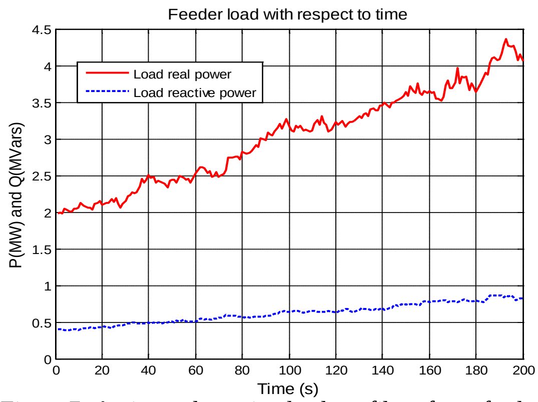

Figure 7: Active and reactive load profiles of test feeder

The load profiles of four selected customers are given in Figure 6, which also demonstrate the non-uniform load characteristic of the test system. Figure 7 shows the load profile of the test system. It is revealed that total energy required in the period under consideration is 167.8 kWh.

B. Tuning of Advanced Line Drop Compensator

Three tuning methods of LDC are tested with a radial feeder in Figure 4 with 69 load buses on the back bone. For this test, distances between load buses are assumed to increase with respect to the distance of load from the substation. This assumption is made to reflect the lower density of load in the remote area and also to examine the LDC's accuracy. Moreover, let us assume that load demand of customers is changing with time using the normal distribution. At every instant of time step, there is o_1% of customer varying their loads with o_2% randomization. Simulations have been carried out with different values of 'o_1' and 'o_2' to investigate the performance of the LDC.

Figure 8 shows the performance of three types of LDC's tuning in comparison to the direct measurement. In this case, o_1 = 20% and o_2 = 25% are applied. It should be noted that the load dynamic in this simulation is modeled as a linear ramp of the mean load. The load profile used in this simulation is provided in Figure 9.

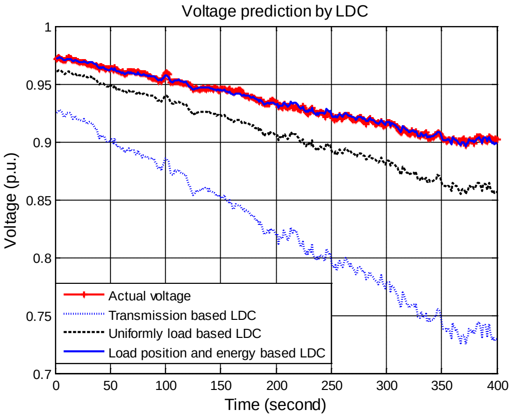

Figure 8: Voltage predictions using different methods of LDC tuning

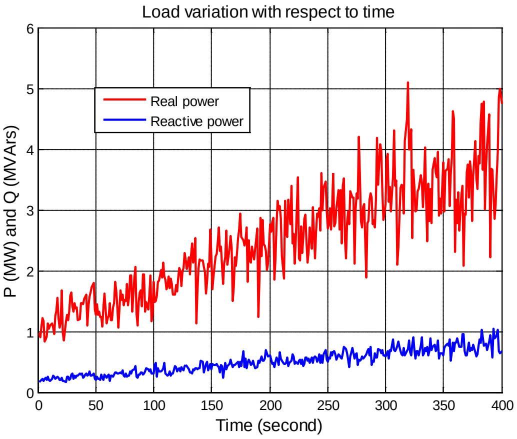

Figure 9: Load variation with respect to time for the LDC test

Figure 8 reveals that the proposed tuning method is the best one, which gives relatively accurate prediction of the remote end voltage. The uniformly load based LDC has some level of discrepancy compared to the actual one due to highly non-uniformly load model using in the test case. The transmission based LDC gives a significant error in prediction (the reason of which is explained in Section II). Table 1 shows the summary of the errors in Root-Mean-Square (RMS) of voltage prediction with different levels of 'o_1' and 'o_2'.

In Table 1, we can see that the errors increase with the increasing of randomization level in all three types of tuning. However, the proposed tuning method gives smallest errors and thus should be used if high accuracy of voltage prediction is required. Also, from the 3rd test scenario ($o_1 = o_2$=50%), we can conclude that if the system load is roughly uniformly distributed, the uniformly load based tuning method will give similar level of accuracy as provided by the proposed tuning method. However, this is rare and loads are not uniformly distributed in practice. The proposed tuning approach is applicable for all conditions.

TABLE 1: ERRORS IN RMS FOR THREE METHODS OF LDC TUNING

		Transmission based LDC	**Uniformly case based LDC**	**Load position and energy based LDC**
Decreasing density of load	o_1 = 20% and o_2 = 25%	5.3558	0.3145	0.0008
	o_1 = 20% and o_2 = 50%	5.4251	0.3204	0.0040
	o_1 = 30% and o_2 = 50%	5.5767	0.3444	0.0054
	o_1 = 50% and o_2 = 50%	5.6040	0.3449	0.0062
Uniform density of load	o_1 = 50% and o_2 = 50%	2.9571	0.0047	0.0041

C. Coordinated Control for a Single DG System

Power generation by a single DG is limited to 15% penetration. The term "penetration" represents the ratio of the DG capacity to the peak load. Simulations have been conducted in two cases: (Case 1) DG has the delay time of 3 seconds for the first decision and then responds instantly for subsequent changes; (Case 2) DG is designed to respond at every instant to the voltage error signal; in other words, DG control action has no time delay.

The voltage reference of LDC for the OLTC is 0.976 p.u. and the reference for the DG is 0.956 p.u. The reference voltage of LDC at the OLTC is set relatively high due to two main reasons:

- For the purpose of maximizing the usage of tap.
- The voltage prediction of LDC at the OLTC is less effective. This is the result of the inclusion of DG as well as the characteristic of the LDC used. The farther the LDC from the remote end, the less accurate the voltage prediction.

Fig.10 shows the tap position to control the voltage level, which remains the same for the delayed and non-delayed DG cases. For both cases, the OLTC acts to compensate remote end voltage by the prediction of the LDC. As the load increases, the tap ratio also increases until it reaches its saturated state. We also note that even though the tap upper limit is 1.1, tap ratio stops increasing at approximately 1.06. This is due to the voltage constraint at the secondary side of the transformer and no further tapping-up can take place when the voltage is at 1.05 p.u.

The power injections from the DG in case 1 (delayed DG) and case 2 (non-delayed DG) have been plotted in Fig.11. It should be noted that the ratio of the DG real and reactive power is always kept constant at 1.78 for maximum voltage change effectiveness [10]. In other words, DG is always operating at power factor of 0.87. As can be seen from Fig.11, the generator in case 2 (non-delayed DG) reacts immediately to compensate any voltage errors, thus operating for a longer period compared to case 1 (delayed DG). For example at t = 190 seconds, the non-delayed DG jumps up to 0.4 MVA and falls down to 0.3 MVA in 4 seconds. On the other hand, the delayed DG responses later and avoids operating for the sudden rise of load. It, therefore, increases to 0.31 MVA only and settles down at that level. As the result, a better voltage profile can be expected in case 2. By using the control scheme, either with non-delayed or delayed DG, the DG is turned ON to provide extra support to the network voltage only in two scenarios: when the tap has not yet reached the desired level due to its delay time, or when no further taping-up is permitted. Otherwise, the voltage is mostly regulated by the OLTC. This can be considered as economically viable solution as the OLTC operation is maximized, while the DG, whose operation is much more expensive, works only in a real need.

In Fig.12, remote end voltage profiles without DG, with DG, and voltage predictions at two regulation points are illustrated graphically for case 1. Similar sets of graphs as the result of non-delayed DG inclusion (case 2) are shown in Fig.13. These figures obviously indicate that the time period for under-voltage with the non-delayed DG is small compared to the case of the delayed DG. Also, by observing the remote end voltage with and without DG in both cases, we can see that the DG has made a considerable contribution to the control of system voltage.

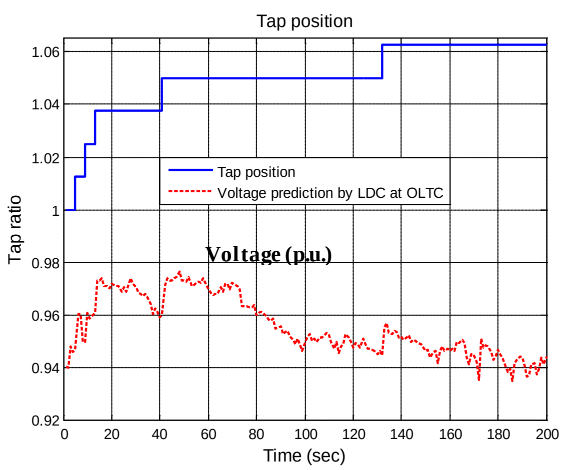

Figure 10: Tap position in case of delayed and non-delayed DG to support feeder load and voltage prediction at OLTC by the proposed tuning approach

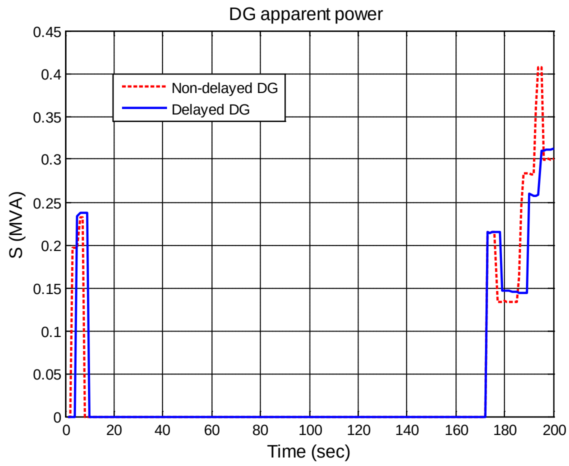

Figure 11: DG power injection with delayed and non-delayed DG

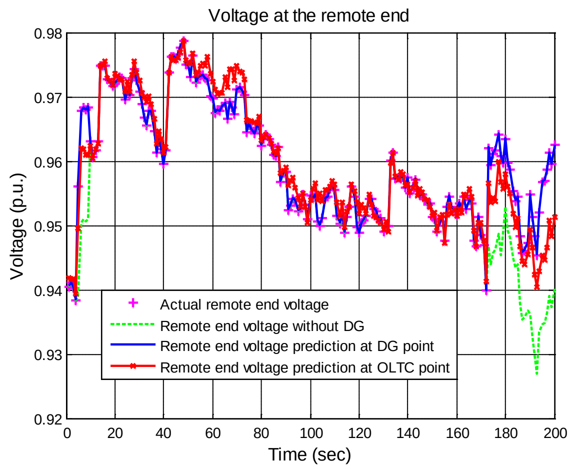

Figure 12: Remote end voltage with respect to time for the case of delayed DG

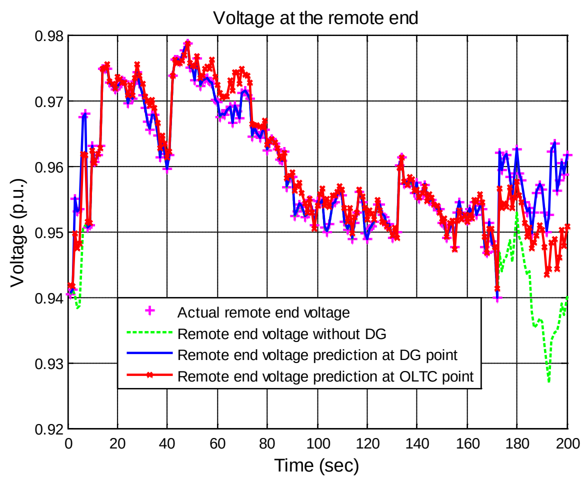

Figure 13: Remote end voltage with respect to time for the case of non-delayed DG

For a more detailed comparison between the two cases, their performances have been evaluated and reported in Table 2. In case 1, the non-delayed DG characteristic makes it working harder, thus provides a better voltage profile with less percentage of customers suffering from under voltage problem compared to case 2. However, the running cost of the DG system in this case is more expensive. Moreover, in several situations, the control scheme in case 1 may cause the DG to switch ON and OFF more frequently than that of case 2. To certain types of DG systems (for which the start/stop penalty [19] is high), this will also raise the total operating cost of the DG system. Thus, the best control scheme needs to be carefully selected in trade-off among the different priorities. If it is very important to maintain the network voltage within the specification, a non-delayed DG will perform better. Otherwise, a DG with some time delay will be more suitable as an economic choice.

TABLE 2: COMPARISON BETWEEN DELAYED AND NON-DELAYED DG SYSTEMS

	Customer-minute under voltage as percent of total customer-minute	DG kWh as percent of total load
Delayed DG (Case 1)	2.2%	1.06% (1.78 kWh)
Non-delayed DG (Case 2)	1.2%	1.12% (1.87 kWh)

As discussed earlier, it is actually simpler to control the regulators (i.e. OLTC or DG) by using their local voltages. However, this process may result in more expensive operation cost of the system. Simulation has been carried out to verify the choice of the control using LDC. Both OLTC and DG are set to be controlled by their local voltages. In case 1, customer minutes under-voltage as fraction of total time is 2.2%, whereas it is 1.2% in case 2. The results show that the total DG energy in case 2 is 1.87 kWh, which is higher than the DG energy (i.e. 1.78 kWh) in case 1. This means that in case 2 the DG will work more often, as well as having a higher running cost compared to case 1.

D. COORDINATED CONTROL FOR MULTIPLE DG SYSTEM

Two DGs have been integrated into the test feeder; DG1 is located at bus 50 while DG2 is located at the remote end bus. The DG1 and DG2 have the capacity of 5% and 10% penetration, respectively.

Both voltage control schemes (i.e. non-communication and minimum communication schemes) have been applied on the same load data to examine their responses. Moreover, to compare the performance of the two methods, they have been adjusted (with their controller constants and voltage reference levels) so that the same voltage quality level of the supply is produced. In both cases, the total customer minute under voltage as percent of total customer-minute is at 2.9%. Figure 14 shows the tap response for both control schemes (with and without communication). The figure reveals that the tap response using no communication system shows a slightly slower response compared to the communication based control scheme. In both control technique, the maximum tap ratio is found to be around 1.05 only, even though its maximum capacity is at 1.10. The reason of this is that the tap cannot increase any further to keep the voltage at the secondary side of the OLTC within the specified limits.

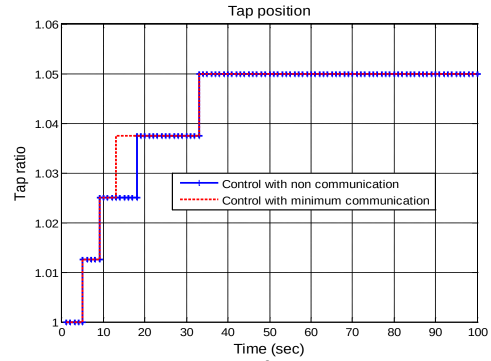

Figure 14: The tap responses for two control schemes

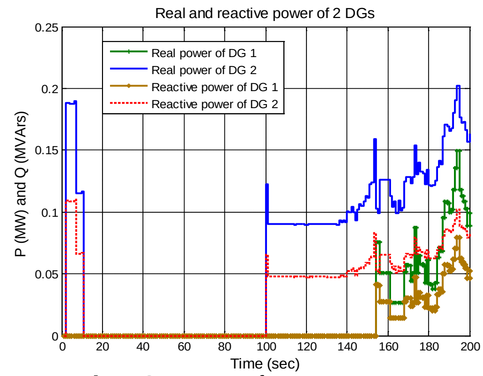

Figure 15: The DG response for non-communication voltage control

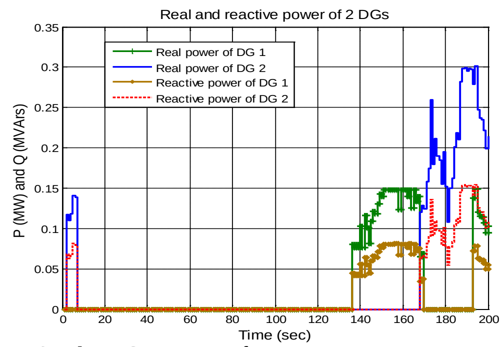

Figure 16: The DG response for minimum communication voltage control

Figures 15 and 16 show the DG responses for the non-communication and minimum communication control schemes, respectively. In the first control technique (Figure15), the DG units operate in two periods of time, firstly when the tap has not reached its desire level (due to time delay), and secondly when the tap is saturated and cannot be increased any further. Also, it can be obviously seen from the figure that the operation time of DG2 is always much higher than that of DG1 because of its higher level of contribution for voltage correction. The DG response of the control technique with communication, given in Figure 16, shows more complicated operation of the two DGs. At the beginning, only DG2 operates to compensate the voltage for its high level of contribution. However, in the later part of the simulation, DG1 starts first and runs for approximately 35 seconds. The reason of this is that during this time, the desired output of DG is not large enough to turn DG2 ON. When the demand increases furthermore, DG2 starts working and DG1 is switched OFF while passing its duty to DG2. Finally, both DG units are switched ON to contribute to the voltage control process.

Table 3 shows the summary of DG output in kWh for each type of controllers. It can be seen from Table 3 that the total DG output for the control without communication is higher than that of the control using communication. This means that it is less expensive in term of the DG operational cost to use the control using communication.

TABLE 3: COMPARISON BETWEEN NON-COMMUNICATION AND MINIMUM COMMUNICATION BASED CONTROL SCHEMES

		Non-communication	Minimum communication
Different DG sizes	DG1	0.88 kWh	1.41 kWh
	DG2	3.63 kWh	2.11 kWh
	Total energy	4.51 kWh	3.52 kWh
Same DG size	DG 1	0.79 kWh	0.49 kWh
	DG 2	3.36 kWh	2.83 kWh
	Total energy	4.15 kWh	3.32 kWh

As shown in Table 3, if two equal-sized DG units (each with 7.5% penetration) are placed in the system at the same positions which are at bus 50 and the remote bus, the communication method also shows more advantage in term of DG running cost. The only different is, in the last 60 seconds of the simulation, DG2 will start first and DG1 will only takes part in the control process when the demand has increased higher than the capacity of the DG1 itself.

Another advantage of the control using minimum communication over the other method can be counted on the stabilization process of the controller, as given in Figures 17 and 18. We can see that it takes only 7 iterations for the communication based control scheme to be stabilized, while it is approximately 24 iterations for the non-communication based control scheme. However, as mentioned earlier, this type of controller involves in a certain level of communication, which is fairly costly. Therefore, an economically effective controller can only be achieved if a good trade-off is made between the cost of communication system and DG running cost. DG-DG interaction and control stabilization have been thoroughly discussed in the earlier work of the authors [18 - 21] in the context of network voltage support.

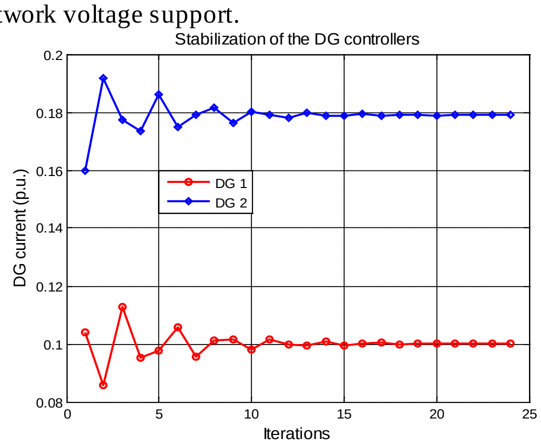

Figure 17: Stabilization of the DG controllers in non-communication scheme

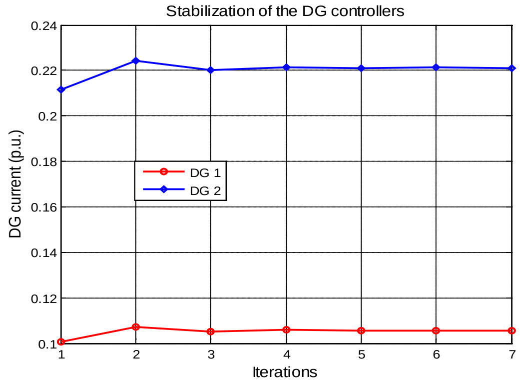

Figure 18: Stabilization of the DG controllers in minimum communication scheme

VI. CONCLUSION

This paper discusses three different tuning methods for LDC. Two available methods: Transmission-based LDC and Uniformly load based LDC are revisited and compared to the new developed technique.

The comparative study reveals that

a) Transmission-based LDC is the least accurate method yet requires minimal knowledge of the system. This method can be improved by integrating a tuning factor which scales the prediction to match more closely to the real voltage. The tuning factor is highly sensitive to the condition of system load and can be determined by online trial and error.

b) Uniformly load based LDC is relatively accurate when system load is roughly uniformly distributed.

c) Load position and energy-based LDC is the most accurate method. It, however, involves in reasonably more detailed knowledge of load position and energy consumption.

This paper has also presented a coordinated control approach for voltage control using the proposed advanced LDC that can effectively coordinate the responses of voltage regulators (or tap changers) and DG units. The proposed advanced LDC can predict voltage more accurately and precisely, and make appropriate decision for the control actions of the regulating devices. Also, the proposed LDC avoids the risk of ineffective selection for the internal setting as in the case of conventional LDC. The proposed control scheme is developed based on the protection principles, such as magnitude grading and time grading. This has greatly improved its performance by increasing the capacity of the tap changer and using the DG more effectively. It also minimizes the interaction level among the controllers of regulating devices and DG units. In addition, the proposed control system avoids the unnecessary operation of the tap changer and DG units. The comparison of delayed and non-delayed DG and also the comparison of the control techniques with and without using communication presented in this paper offer valuable information to the network operators for selecting the most suitable control system, to satisfy the utility and the customers' requirements.

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REFERENCES

[1] "Guide for the Connection of Embedded Generation in the National Electricity Market" by Australian Business Council for Sustainable Energy, September 2003.

[2] "A National Code of Practice for Embedded Generation – Consultation paper" by PB Associates, February 2006.

[3] R. O'Gorman, and M.A. Redfern, "Voltage Control Problems on Modern Distribution Systems", *2004 IEEE Power Engineering Society General Meeting*, 6-10 June 2004, Vol.1, pp. 662 – 667.

[4] E. Carpaneto, G. Chicco, M. De Donno, and R. Napoli, "Voltage Controllability of Distributed Systems with Local Generation Sources", *Bulk Power System Dynamics and Control – VI*, 22-27 August 2004, Cortina d'Ampezzo, Italy, pp. 261 – 273.

[5] H.M. Ma, K.F. Man, and D.J. Hill, "Control Strategy for Multi-objective Coordinate Voltage Control Using Hierarchical Genetic Algorithms", *IEEE International Conference on Industrial Technology, ICIT 2005*, 14-17 Dec. 2005, pp. 158 – 163.

[6] F.A.B. Lemos, L.C. Werberich, J.S. Freitas, and M.A. da Rosa, "A Strategic for Voltage Coordinated Control to Improve System Operation", *2001 IEEE Porto Power Tech Proceedings*, 10-13 Sept. 2001. Vol. 2.

[7] D. Rho, H. Kita, J. Hasegawa, and K. Nishiya, "A Study on the Optimal Voltage Regulation Methods in Power Distribution Systems Interconnected with Dispersed Energy Storage and Generation Systems", *Proceedings of EMPD '95., 1995 International Conference on Energy Management and Power Delivery*, 1995, 21-23 Nov. 1995, Vol. 2, pp. 702 – 707.

[8] R. Baldick and F.F. Wu, "Efficient Integer Optimization Algorithms for Optimal Coordination of Capacitors and Regulators", *IEEE Transactions on Power Systems*, Aug. 1990, Vol. 5, Issue 3, pp. 805 – 812.

[9] L.A. Kojovic, "Coordination of Distributed Generation and Step Voltage Regulator Operations for Improved Distribution System Voltage Regulation", *2006 IEEE Power Engineering Society General Meeting*, 18-22 June 2006.

[10] An D.T. Le, M.A. Kashem, M. Negnevitsky and G. Ledwich, "Minimizing Voltage Deviation in Distribution Feeders by Optimizing Size and Location of Distributed Generation", AUPEC 2005 Conference, Tasmania, Australia, 25-28 September, 2005, Vol. 2.

[11] T.E. Kim, and J.E. Kim, "Voltage Regulation Coordination of Distributed Generation System in Distribution System", *IEEE Power Engineering Society Summer Meeting*, 15-19 July 2001, Vol. 1, pp. 480 – 484.

[12] L. Kojovic, "Impact of DG on Voltage Regulation", *IEEE Power Engineering Society Summer Meeting*, 2002, Vol. 1, pp. 97 – 102.

[13] Choi Joon-Ho, and Kim Jae-Chul, "Advanced Voltage Regulation Method of Power Distribution Systems Interconnected with Dispersed Storage and Generation Systems", *IEEE Transactions on Power Delivery*, April 2001, Vol. 16, Issue 2, pp. 329 – 334.

[14] G.W. Kim, and K.Y. Lee, "Coordination Control of ULTC Transformer and STATCOM Based on an Artificial Neural Network", *IEEE Transactions on Power System*, May 2005, Vol. 20, Issue 2, PP. 580 – 586.

[15] J.H. Harlow, "Load Tap Changing Control", *National Rural Electric Cooperative Association (NRECA)*, 24 March 1996, Houston, Texas, USA.

[16] An D.T. Le, K. M. Muttaqi, M. Negnevitsky and G. Ledwich, "Applying protection principles for controlling distributed generation", Australian Journal of Electrical and Electronics Engineering, Vol.4, No.3, 2007.

[17] K. M. Muttaqi, An D.T. Le, M. Negnevitsky and G. Ledwich, "A Coordinated Voltage Control Approach for Coordination of OLTC, Voltage Regulator, and DG to Regulate Voltage in a Distribution Feeder" IEEE Trans. On Industry Applications, Vol. 51, No. 2, 2015, pp.1239-1248.

[18] M. A. Kashem and G. Ledwich, "Distributed Generation as Voltage Support for Single Wire Earth Return Systems", IEEE Trans. On Power Delivery, Vol. 19, No. 3, 2004, pp. 1002-1011.

[19] M. A. Kashem and G. Ledwich, "Multiple Distributed Generators for Distribution Feeder Voltage Support", IEEE Trans. on Energy Conversion, Vol. 20, No. 3, 2005, pp.676-684.

[20] D. Ranamuka, A. Agalgaonkar, and K. M. Muttaqi, "Online Voltage Control in Distribution Systems with Multiple Voltage Regulating Devices", IEEE Transactions on Sustainable Energy, Vo. 5, No. 2, 2014, pp.617-628.

[21] K. M. Muttaqi, A. D. T. Le, M. Negnevitsky, G. Ledwich, "An Algebraic Approach for Determination of DG parameters to Support Voltage Profiles in Radial Distribution", IEEE Transactions on Smart Grid, Vol. 5, No .3, 2014, pp.1351-1360.

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