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Minimising power losses in distribution systems with distributed resources

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Abstract

Attempts to reduce electricity cost, together with improving the efficiency of distribution systems, have led power utilities to dealing with the problem of power loss minimisation. Although losses in the system can never be entirely eliminated, they can be controlled and minimised in several ways. Research conducted in the last few decades has proven that an inclusion of Distributed Resources (DR) into distribution systems considerably lowers the level of power losses. Moreover, the choice of DR is even more attractive since it provides not only benefits in power loss minimisation, but also a wide range of other advantages including environment, economic and technical issues. In this paper, the potential ability of DR in power loss reduction is discussed. A novel approach to determining a proper size and location of DR in order to achieve maximum loss reduction in distribution feeders is developed. A practical feeder of Aurora Energy, Tasmania is selected to demonstrate the effectiveness of the proposed method and the simulation results are reported.

Keywords

resources, losses, distributed, power, systems, minimising, distribution

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Minimising Power Losses in Distribution Systems with Distributed Resources

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ABSTRACT

Attempts to reduce electricity cost, together with improving the efficiency of distribution systems, have led power utilities to dealing with the problem of power loss minimisation. Although losses in the system can never be entirely eliminated, they can be controlled and minimised in several ways. Research conducted in the last few decades has proven that an inclusion of Distributed Resources (DR) into distribution systems considerably lowers the level of power losses. Moreover, the choice of DR is even more attractive since it provides not only benefits in power loss minimisation, but also a wide range of other advantages including environment, economic and technical issues. In this paper, the potential ability of DR in power loss reduction is discussed. A novel approach to determining a proper size and location of DR in order to achieve maximum loss reduction in distribution feeders is developed. A practical feeder of Aurora Energy, Tasmania is selected to demonstrate the effectiveness of the proposed method and the simulation results are reported.

Index Terms -- Distributed Resources, Distribution System, Optimal Size, Optimal Location, Power Loss.

1. INTRODUCTION

One of the most common indications of evaluating the efficiency of a power system is the ratio of power loss to the total generating power. The system is considered as efficient when the loss level is low. There are many factors that may affect the power losses in the distribution networks such as [1]: (i) number and characteristics of electrical device i.e. transformers, conductors, regulators, etc., (ii) parameters of transmission lines i.e. length, type, size, material of cables, etc., (iii) types of connected loads in the system, (iv) network configuration, (v) voltage and current conditions in the system, etc. Among those factors, power losses associated with distribution lines take a major part in the overall power losses. Moreover, taking into account the fact that Tasmania has many long distribution feeders, especially in the rural areas, the losses in distribution lines are even more significant. Thus, in order to gain a better performance of electricity supply service, loss minimisation techniques are drawing more attention.

Reduction of power losses by Distributed Resources (DR) is becoming a popular technique worldwide. Since an integration of DR into distribution systems will alter the power flows, it is obvious that the power losses in the system are affected [2]. DR is utilised for improving the system voltage profile, power quality, system reliability and security, etc. From the economy point of view, the size of DR is small compared with the size of centralised generation. This makes the DR easier to install; and it requires less capital investment as well as operating and maintenance cost. Deferring of Transmission and Distribution facility upgrades is also possible with the inclusion of DR. Many individual customers have used DR as a co-generation system [3]. Such systems can utilise waste from industrial process such as waste water, waste wood, etc. to generate electricity. Also, the heat released from this transformation procedure can be used for heating or boiling water. Normally, the DR has a limited size from a few kW to a few MW and located at the end of the feeder. However, the choice of the DR location, level of penetration as well as the type of DR can significantly vary the effects of the DR on a distribution system [4]. For this reason, studies of the optimal size and location of DR to maximise DR benefits are necessary.

Many researches have been working in the DR field to minimise power losses in distribution systems. Authors in [5] have presented an algorithm to determine a near optimal location of the DR with respect to system losses. In [6], an optimisation model has been developed through constrained power flows and DR citing. In [7], a methodology for evaluating the effects of DR sizing and sitting in terms of reliability, losses and voltage profile has been introduced. Authors in [8] have presented analytical methods to determine a placement of the DR for minimum power losses in radial and networked systems. In [9], the DR allocation is discussed based on the network reconfiguration and loss reduction.

This paper presents a methodology to determine an optimal size and location of the DR toward loss minimisation. The level of DR contribution to loss reduction is investigated according to the level of DR penetration. A technique for computing the contribution of DR in reduction of power losses has been developed. The proposed method is tested on a practical distribution system to demonstrate its effectiveness and accuracy.

2. MODELLING OF DISTRIBUTION NETWORKS WITH DISTRIBUTED RESOURCES

An inclusion of DR into distribution systems significantly affects system configuration as well as the operating conditions of the system. It is important for the utility to ensure that the voltage at every load bus in the system does not exceed an acceptable range of 6%. For this reason, the system bus voltages are considered in all conditions, with and without DR.

There are many methods that can be used to evaluate the state of the system, such as Newton-Raphson, Gauss-Seidel, Optimal Load Flow, Distflow, etc. Since we are only interested in the voltage levels of distribution system, our work may be considerably reduced. In this section, a methodology to compute voltages of a system, with DR connection, is presented. The method has been developed based on a basic network's equation.

Consider a distribution system with N load buses. These buses are denoted from bus 1 to bus N, from the sending end to the receiving end of the feeder, respectively. As the DR location may vary, we introduce an additional bus into the system. The DR consists of a generating source connected to this additional bus. The bus N+1 is connected to a load bus of the system through the DR impedance. The relationship between voltages and currents in the system is as follows,

$$\mathbf{Y_{bus}}\mathbf{V_{bus}} = \mathbf{I_{bus}} \tag{1}$$

where $\mathbf{Y_{bus}}$ is the impedance matrix for (N+1) bus system., $\mathbf{V}$ is the vector of voltages for bus 1 to bus (N+1), and $\mathbf{I}$ is the vector of currents for bus 1 to bus (N+1).

Eq.(1) can be written as,

$$\left[\begin{array}{c|ccc|c} Y_{1,1} & Y_{1,2} & \cdots & Y_{1,N} & Y_{1,N+1} \\ \hline Y_{2,1} & Y_{2,2} & \cdots & Y_{2,N} & Y_{2,N+1} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ Y_{N,1} & Y_{N,2} & \cdots & Y_{N,N} & Y_{N,N+1} \\ \hline Y_{N+1,1} & Y_{N+1,2} & \cdots & Y_{N+1,N} & Y_{N+1,N+1} \end{array}\right] \left[\begin{array}{c} V_1 \\ \hline V_2 \\ \vdots \\ V_N \\ \hline V_{N+1} \end{array}\right] = \left[\begin{array}{c} I_1 \\ \hline I_2 \\ \vdots \\ I_N \\ \hline I_{N+1} \end{array}\right] \tag{2}$$

Eq.(2) can be partitioned into sub-matrices as,

$$\begin{bmatrix} \mathbf{Y_A} & \mathbf{Y_B} & \mathbf{Y_C} \\ \mathbf{Y_B^T} & \mathbf{Y_D} & \mathbf{Y_E} \\ \mathbf{Y_C^T} & \mathbf{Y_E^T} & \mathbf{Y_F} \end{bmatrix} \begin{bmatrix} \mathbf{V_1} \\ \mathbf{V_Y} \\ \mathbf{V_{N+1}} \end{bmatrix} = \begin{bmatrix} \mathbf{I_1} \\ \mathbf{I_Y} \\ \mathbf{I_{N+1}} \end{bmatrix} \tag{3}$$

where,

$\mathbf{Y_A} = Y_{1,1}$ $\mathbf{Y_B} = \begin{bmatrix} Y_{1,2} & \ldots & Y_{1,N} \end{bmatrix}$ $\mathbf{Y_C} = Y_{1,N+1}$

$$\mathbf{Y_D} = \begin{bmatrix} Y_{2,2} & \ldots & Y_{2,N} \\ \vdots & \ddots & \vdots \\ Y_{N,2} & \ldots & Y_{N,N} \end{bmatrix} \quad \mathbf{Y_E} = \begin{bmatrix} Y_{2,N+1} \\ \vdots \\ Y_{N,N+1} \end{bmatrix} \quad \mathbf{Y_F} = Y_{N+1,N+1}$$

$$\mathbf{V_Y} = \begin{bmatrix} V_2 \\ \vdots \\ V_N \end{bmatrix} \quad \text{and} \quad \mathbf{I_Y} = \begin{bmatrix} I_2 \\ \vdots \\ I_N \end{bmatrix}$$

According to our definition, the system's utility is connected to bus 1 and the DR is connected to bus N+1. Therefore,

$$\mathbf{I_Y} = \mathbf{0},\ V_1 = V_S,\ V_{N+1} = V_{DR} \text{ and } I_{N+1} = I_{DR}$$

By substituting those values into Eq.(3), we have:

$$\begin{bmatrix} \mathbf{Y_A} & \mathbf{Y_B} & \mathbf{Y_C} \\ \mathbf{Y_B^T} & \mathbf{Y_D} & \mathbf{Y_E} \\ \mathbf{Y_C^T} & \mathbf{Y_E^T} & \mathbf{Y_F} \end{bmatrix} \begin{bmatrix} V_S \\ \mathbf{V_Y} \\ V_{DR} \end{bmatrix} = \begin{bmatrix} I_S \\ \mathbf{0} \\ I_{DR} \end{bmatrix} \tag{4}$$

Equations related to source voltage and the DR bus voltage can be extracted from Eq.(4) as follows:

$$\mathbf{V_Y} = -\mathbf{Y_D}^{-1}\left(\mathbf{Y_B^T}V_S + \mathbf{Y_E}V_{DR}\right) \tag{5}$$

$$\mathbf{Y_F}V_{DR} = I_{DR} - \left(\mathbf{Y_C^T}V_S + \mathbf{Y_E^T}\mathbf{V_Y}\right) \tag{6}$$

By substituting $\mathbf{V_Y}$ from Eq.(5) into Eq.(6), we get:

$$\mathbf{Y_F}V_{DR} = I_{DR} - \mathbf{Y_C^T}V_S + \mathbf{Y_E^T}\mathbf{Y_D^{-1}}\left(\mathbf{Y_B^T}V_S + \mathbf{Y_E}V_{DR}\right) \tag{7}$$

Since utility voltage is kept constant at the nominal level, V_S always has a value of 1.0 p.u. Substituting V_S = 1 into Eq. (7) and rearranging it, we obtain:

$$V_{DR} = \left(\mathbf{Y_F} - \mathbf{Y_E^T}\mathbf{Y_D^{-1}}\mathbf{Y_E}\right)^{-1}\left(I_{DR} - \mathbf{Y_C^T} + \mathbf{Y_E^T}\mathbf{Y_D^{-1}}\mathbf{Y_B^T}\right) \tag{8}$$

By substituting Eq.(8) into Eq.(5), we get

$$\mathbf{V_Y} = -\mathbf{Y_D^{-1}}\begin{bmatrix} \mathbf{Y_B^T} + \mathbf{Y_E}\left(\mathbf{Y_F} - \mathbf{Y_E^T}\mathbf{Y_D^{-1}}\mathbf{Y_E}\right)^{-1} \\ \left(I_{DR} - \mathbf{Y_C^T} + \mathbf{Y_E^T}\mathbf{Y_D^{-1}}\mathbf{Y_B^T}\right) \end{bmatrix} \tag{9}$$

The voltages from bus 2 to bus N of the system due to the current injected by the DR can be computed by Eq.(9).

By substituting I_{DR} = 0, we obtain the voltages of the system without DR:

$$\mathbf{V_Y^{ini}} = -\mathbf{Y_D^{-1}}\left[\mathbf{Y_B^T} + \mathbf{Y_E}\left(\mathbf{Y_F} - \mathbf{Y_E^T}\mathbf{Y_D^{-1}}\mathbf{Y_E}\right)^{-1}\left(-\mathbf{Y_C^T} + \mathbf{Y_E^T}\mathbf{Y_D^{-1}}\mathbf{Y_B^T}\right)\right] \tag{10}$$

The voltage changes at bus 2 to bus N in the system with the DR are calculated by subtracting Eq.(10) from Eq.(9). We get,

$$\Delta\mathbf{V_Y} = -\mathbf{Y_D^{-1}}\mathbf{Y_E}\left(\mathbf{Y_F} - \mathbf{Y_E^T}\mathbf{Y_D^{-1}}\mathbf{Y_E}\right)^{-1}I_{DR} \tag{11}$$

Eq.(11) in matrix form can be shown as,

$$\Delta\mathbf{V_Y} = \mathbf{m}\, I_{DR} \tag{12}$$

where $\mathbf{m}$ is the coefficient matrix of size (N-1) used for calculating the voltage changes from bus 2 to bus N.

Introducing the DR into the system results in new system voltages. These new voltages can be computed either directly by Eq.(10), or by the superposition of the initial voltage and the voltage change for each individual load bus as shown in Eq.(13).

$$\begin{bmatrix} V_S \\ V_2 \\ \vdots \\ V_N \end{bmatrix} = \begin{bmatrix} V_S \\ V_2^{ini} \\ \vdots \\ V_N^{ini} \end{bmatrix} + \begin{bmatrix} 0 \\ m_2 \\ \vdots \\ m_N \end{bmatrix} I_{DR} \quad (13)$$

where V_k^{ini} and V_k are voltages of the system without the DR and with the DR, respectively.

The current injection from the DR should be understood in terms of magnitude and phase. For a pure real injection, the DR current has the same phase with the bus voltage at the DR connection point. For a pure reactive injection, the DR current phase is 90° leading the phase of the bus voltage at the DR connection point. In this paper, we investigate real power loss reduction with a real power injection only introduced by the DR.

3. MAXIMISING LOSS REDUCTION BY DR

Losses in power systems depend on the current flow in the line and also line parameters. The real power loss is I^2r, and the reactive power loss is I^2x. These losses are unwanted due to the fact that they reduce system efficiency and increase cost of electricity. Although system losses are unavoidable, they can be minimised by planning and operating distribution networks in an optimal way.

An integration of the DR into distribution systems contributes significantly to the loss reduction. This is due to the fact that the DR provides local support to the total load, and thus reduces the power flows in the system. Since the system efficiency is usually assessed in term of real power loss [10], only the DR effect on real power loss reduction is considered in this paper.

Real power loss for the system can be calculated as,

$$P_L^{ini} = \sum_{j=1}^{n_{br}} \left| I_j \right|^2 r_j \quad (14)$$

where, n_{br} is total number of branches in the system, $\left| I_j \right|$ is the current magnitude in branch j, and r_j is the resistance of branch j.

The current in the branch k is defined as,

$$I_j = \left(V_{j_a}^{ini} - V_{j_b}^{ini} \right) Y_j \quad (15)$$

where $V_{j_a}^{ini}$ and $V_{j_b}^{ini}$ are voltages at sending end a, and receiving end b of the branch j, respectively; and Y_j is the admittance of branch j.

By substituting Eq.(15) into Eq.(14), we obtain:

$$P_L^{ini} = \sum_{j=1}^{n_{br}} \left| \left(V_{j_a}^{ini} - V_{j_b}^{ini} \right) Y_j \right|^2 r_j \quad (16)$$

The bus voltages change due to the DR inclusion in the system. Therefore, the new power losses of the system will become:

$$P_L = \sum_{j=1}^{n_{br}} \left| \left(V_{j_a} - V_{j_b} \right) Y_j \right|^2 r_j \quad (17)$$

Replacing V_{j_a} and V_{j_b} by $V_{j_a}^{ini} + \Delta V_{j_a}$ and $V_{j_b}^{ini} + \Delta V_{j_b}$, respectively, we obtain:

$$P_L = \sum_{j=1}^{n_{br}} \left| \left[\left(V_{j_a}^{ini} + \Delta V_{j_a} \right) - \left(V_{j_b}^{ini} + \Delta V_{j_b} \right) \right] Y_j \right|^2 r_j \quad (18)$$

Substituting the values of ΔV_{j_a} and ΔV_{j_b} from Eq.(12) into Eq.(18), we obtain:

$$P_L = \sum_{j=1}^{n_{br}} \left| \left[\left(V_{j_a} + m_{j_a} I_{DR} \right) - \left(V_{j_b} + m_{j_b} I_{DR} \right) \right] Y_j \right|^2 r_j \quad (19)$$

By rearranging Eq.(19), we have:

$$P_L = \sum_{j=1}^{n_{br}} \left| \left[\left(V_{j_a} - V_{j_b} \right) + \left(m_{j_a} - m_{j_b} \right) I_{DR} \right] Y_j \right|^2 r_j \quad (20)$$

The active loss reduction of the system due to the DR inclusion can be calculated by subtracting Eq.(20) from Eq.(16):

$$\Delta P_{loss} = \sum_{j=1}^{n_{br}} \left\{ \left| \left(V_{j_a} - V_{j_b} \right) Y_j \right|^2 - \left| \left[\left(V_{j_a} - V_{j_b} \right) + \left(m_{j_a} - m_{j_b} \right) I_{DR} \right] Y_j \right|^2 \right\} r_j \quad (21)$$

Eqs (20) and (21) indicate that the minimisation of losses or the maximisation of loss reduction can be achieved by injecting current from the DR. The maximum loss reduction of the system with the DR at a specific location can be obtained by determining an optimal value of the current injection.

4. DESCRIPTION OF TEST SYSTEM

A practical system is shown in Fig. 1. It is selected from the distribution network of Aurora Energy, Tasmania to test an accuracy and validity of the proposed method. The system reflects common characteristics of the distribution system in Tasmania, where distribution feeders are usually long and radial.

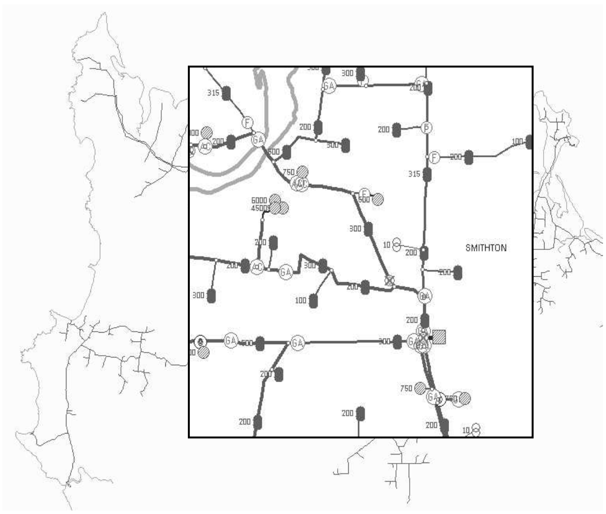

Figure 1: Smithton substation

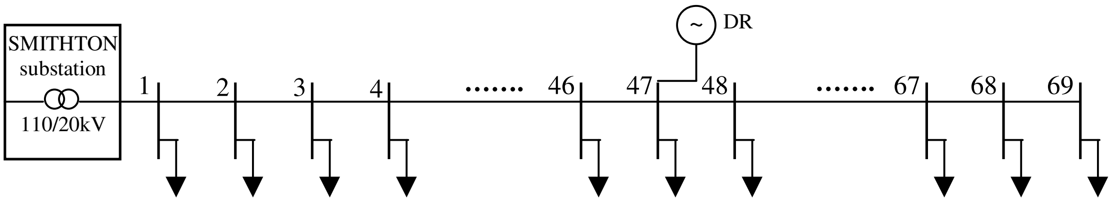

Figure 2: One-line diagram of Smithton substation

The substation has two incoming feeders, each has a step down transformer of 110/22 kV. It has five out-coming feeders called Woolnorth, Arthur River, Edith Creek, Roger River, and Smithton Township. Feeder 5 from Smithton substation to Woolnorth is selected as a test system. The one-line diagram of the system is shown in Fig.2. It has 69 load buses. Line impedance of the feeder is $Z_l = 0.6672 + j0.3745$ Ω/km. Nominal substation voltage V_S is 22 kV. And Thevenin source impedance is $Z_S = 0.7278 + j2.6802$ Ω. The total load of the feeder is 2 MVA. The feeder is assumed to have uniformly distributed loads.

5. SIMULATION RESULTS AND DISCUSSIONS

In this section, effects of the DR size and the DR location on power loss reduction are examined. MATLAB 7.0 is used to conduct the simulations. The MVA base of the system is 1MVA and the voltage base is 22 kV. System without the DG has power loss of 77.5 kW.

5.1. OPTIMISING THE DR LOCATION FOR LOSS REDUCTION

Studies [5-9] reveal that, power losses depend on the location of the DR. Therefore, it is important to consider the DR sitting.

To demonstrate the effect of the DR placement, simulations are carried out with the DR of the 100% penetration. In this case, the DR can support full load in the system. The DR is tested at each load bus in the system one at a time and power losses are recorded for each test. Although it is not realistic to have a DR of the 100% penetration, the simulation is carried out to illustrate the significance of the DR location. Fig.3 shows the decrease of power losses for different DR sittings. Results show that when the DR is moved along the feeder, the system losses are reduced. However, the power losses start to increase with moving the DR toward the end of the feeder. The minimum system loss of 21.7 kW or 72.1% loss reduction is obtained when the DR is located at bus 36. The results obtained are close to the results reported in [5,8]. In [5], the study revealed that when the DR supplies all the loads, the minimum loss is obtained with the DR placed in the middle of the feeder. Also, in [8] the losses are reduced by approximately 75%.

The DRs with the penetration from 1% to 100% are used to test effects of the DR location and the DR penetration in reducing power losses. Fig.4 shows the best placement of the DR in the system for minimum power loss with respect to different sizes of the DR. When the level of penetration is small, minimum system losses are achieved with the DR located at the end of the feeder. As the DR penetration increases, it becomes more effective to place the DR further away from the remote end of the feeder.

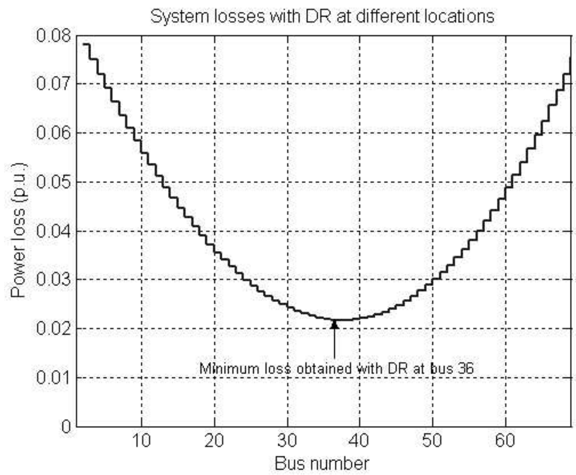

Figure 3: Power losses with the 100% DR penetration at different buses

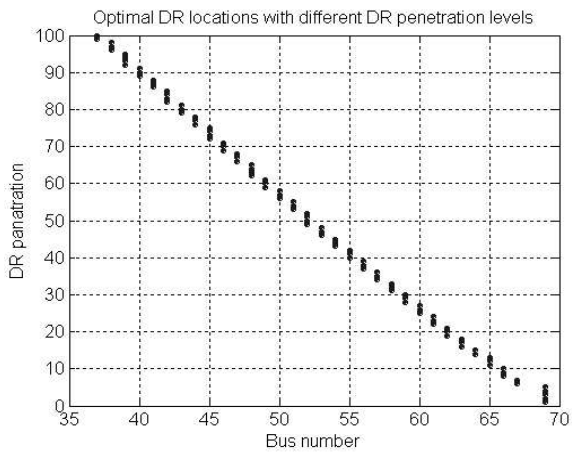

Figure 4: The DR location for minimum power loss with respect to different DR penetration levels

5.2. OPTIMISING THE DR SIZE FOR LOSS REDUCTION

The DR size also effects power losses in a distribution system. This section will determine an optimal size of the DR for a given DR location.

Let us select randomly five load buses 69, 61, 56, 48 and 39 - to study the influence of the DR size on power losses. Fig.5 illustrates the changes of power losses occurring with the change of the DR size. The DR size is expressed in terms of the penetration level. All buses have the same trend in power loss curves with respect to changes in the DR size. The trend is parabolic in shape, which means that the minimum power loss can be obtained with a particular level of the DR penetration.

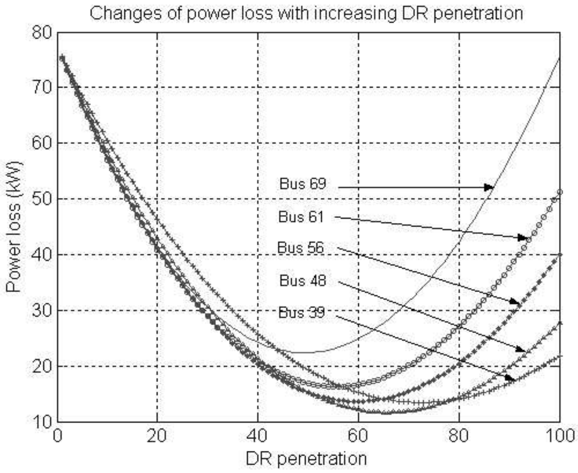

Figure 5: Power loss changes for the DR of different penetration levels

Once again, tests with the DR levels of penetration from 1% to 100% are conducted. For each level, the DR is placed at each load bus, one at a time, and the minimum loss for each level is determined. Fig.6 shows the system losses at the optimal DR location with respect to different DR sizes. Since the power losses are different with different levels of the DR penetration, Fig.6 reveals that the DR size has considerable impact on reduction of power losses in the system.

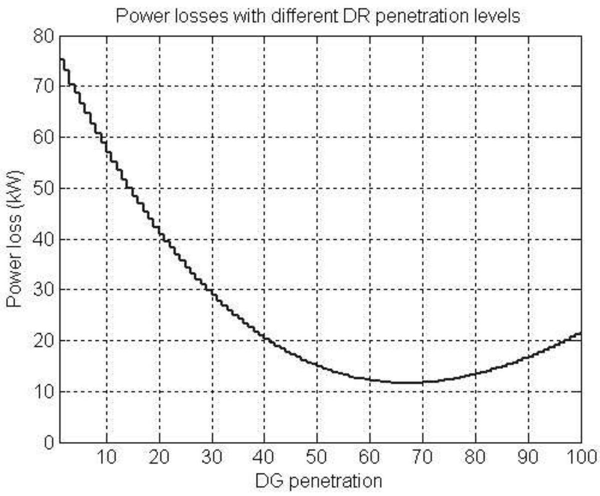

Figure 6: Power losses of DR with different penetration levels

5.3. Optimising Both The DR Size and DR Location for Minimum Power Losses

The results obtained above indicate that both size and location of the DR have effects on the power loss in distribution systems. In Fig.5, we demonstrated that for different DR locations, minimum losses are obtained under different levels of the DR penetration. Also, these minimum loss levels (local minimum) are different from each other. Therefore, we should now obtain minimum power losses with the optimal sets of the DR sizing and sitting.

From Fig.4, we can observe that it is not effective to place the DR close to the substation. Thus, we should consider the DR placements at bus 36 to bus 69. Fig.7 shows the minimum losses obtained for different DR locations and their corresponding optimal sizes. From Fig.7, we can see that an optimal set of the DR size and location are 67% and 47, respectively. If a DR of 67% penetration is installed at bus 47, minimum power loss of 11.6 kW is obtained.

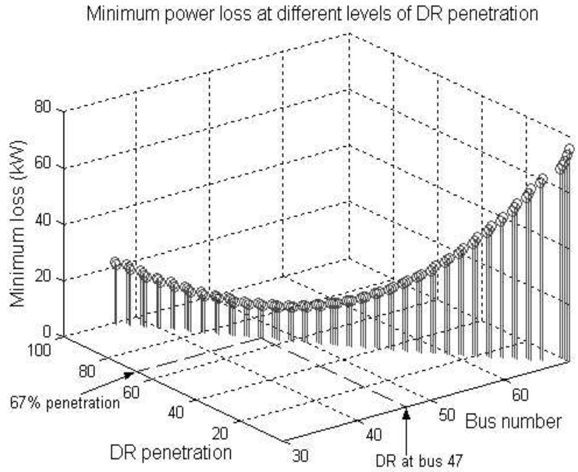

Figure 7: Minimum power losses in terms of the DR penetration level and DR location

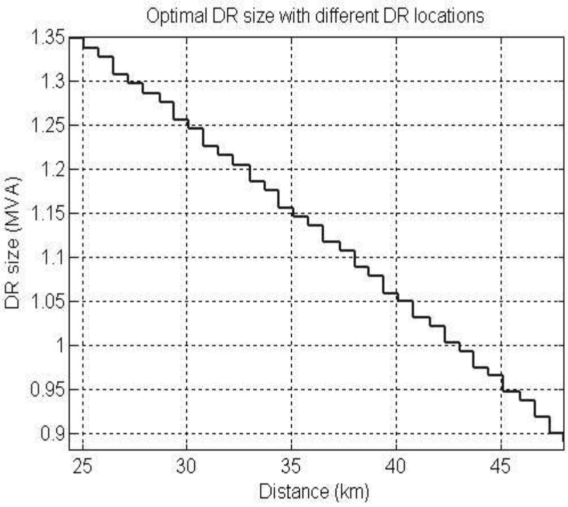

Figure 8: Optimal DR size with respect to the DR location

In reality, it is difficult to place the DR exactly at the optimal location due to the availability of space and fuel, suitability of energy sources, etc. As the result, it can be useful to determine an optimal DR size for a particular DR location. The optimal DR sizes with respect to different DR locations are shown in Fig.8. It can be seen that the closer the DR to the remote end, the smaller the DR size is needed for maximum loss reduction. The DR size optimisation using different DR locations are shown in Fig.9.

Fig.10 shows the voltage profile of the feeder with and without the DR. The DR is of an optimal size and placed at an optimal location. Fig.10 shows that the DR does not only reduce power losses, but also improve the voltage profile of the system. All voltages of load buses are within the acceptable range with the DR included in the system.

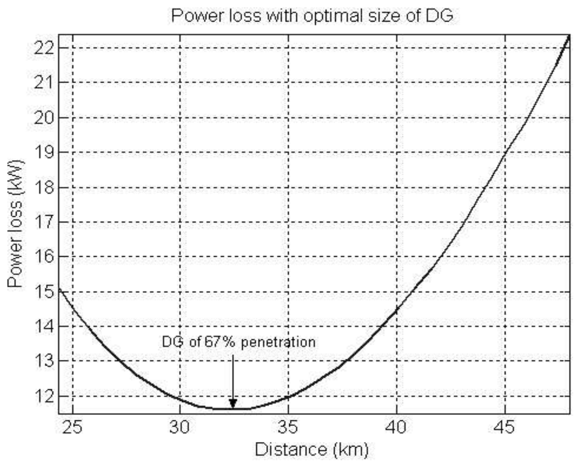

Figure 9: Power losses with the DR of the optimal size

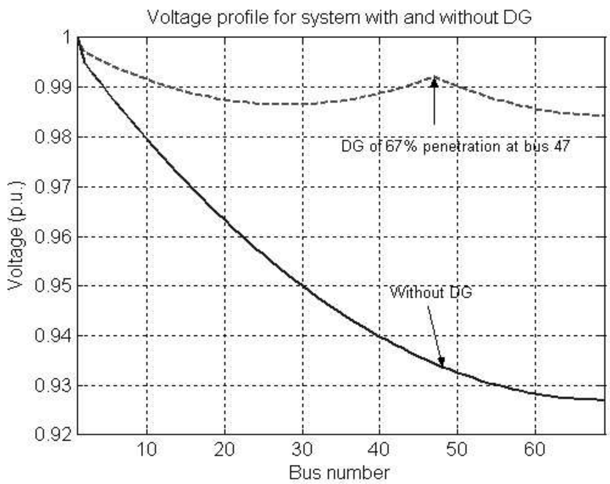

Figure 10: Voltage profile of system with and without DG

6. CONCLUSIONS

This paper discusses the impacts of the DR size and the DR location on the power loss reduction in distribution systems. A methodology to determine an optimal DR size for a particular DR location for minimising power losses is derived. Simulations based optimal sets of the DR size and the DR location for distribution systems are presented. The proposed method is tested on a practical system. The results obtained show that power losses of the system is considerably reduced via the DR integration. A proper DR planning in regards to sitting and sizing of the DR is proven to be important in improving the system efficiency.

7. ACKNOWLEDGMENTS

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