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The impact of smart transformer on different radial distribution systems

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Abstract: The work is intended to extend the application of a smart transformer on a radial distribution system. In this paper, an updated algorithm on the backward/forward power flow is introduced. The so-called direct approach of power flow is employed and analyzed. In addition, the paper focused on integrating a smart transformer to the network and solving the updating network also using the direct approach load flow. The solution of the smart transformer using the direct approach power flow method is quite straightforward. This model is applied to radial distribution systems which are the IEEE 33- and IEEE 69-bus systems as a case study. Also, the paper optimizes the best allocation of the smart transformer to reduce the power losses of the grid.

Key words: smart transformer, smart grid, direct approach, power flow, power loss reduction

1. Introduction

The proliferation and ever-growing of the renewable energy sources and the appearance of recently upgradable loads as an electric vehicle (EV) and its charging stations may cause some of operational and technical challenges for the distribution systems [1]. That refers to their attractive prices and the policies which provide facilities to the users. As already mentioned in the above specifications, the end stakeholders are not only electricity consumers but also producers in some cases. The genuine distribution network restricts wide utilization of renewable energy resources, provides poor EV foundation, and relies on unidirectional data flow between sources and control centers. The power electronic may perform an important role regarding this area to improve



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the distribution system. Indeed, most of the grid components are connected through power converters. To enhance the system reliability and keep the system stability the power electronic presents solutions and capabilities like an active filter, flexible ac transmission systems (FACTS), DC high-voltage, electronic breakers and solid-state transformers [2, 3]. Now, the applicability to deliver a high voltage and current with low losses is done through the recent generation of semiconductor devices based on silicon material.

As for the power system perspective and the utilization of power electronics solutions, the updated technologies allow for wide control of the power flow under different conditions. Moreover, these components contribute to making it applicable to implement widely discussed smart grids that execute information and communication technology (ICT) to distribution network operation and planning [4]. Based on power electronics, the smart transformer (ST) can play an important role by utilizing multiple functions and introducing an ancillary service. The concept of the smart transformer (ST) has been investigated for the first time with project of Highly Efficient and Reliable Smart Transformer [5]. MIT in 2011 has selected the smart transformer as one of the emerging technology breakthroughs that has a chance to create a great global effect [6]. Despite that the smart transformer could not be the only solution for the smart grid problems. So, the online coordination between the system components is highly needed to increase the response to prevent the disruptive events like a cyber-attacks and cascading failure.

In addition, the smart transformer can present some new solutions for the industry sector [7]. Smart transformer specifications and the availability of DC links in the smart transformer can control different levels of harmonics, in addition supply different loads with DC or at variable frequencies [8].

Minimizing power losses in the distribution systems is a must as these networks suffer from a huge amount of power losses. The minimization of power losses is done by using distributed generations as a solution to this problem. Distributed generation (DG) presents optimal solution for such a problem, in addition, optimizing the best location of the DG in the distribution system enhances the voltage profile of the network. That make the researchers focus in recent years on exploring other aspects of power system like reliability stability and protection.

In this paper, a model of the smart transformer is introduced for self-repair of the smart grid. The self-healing of the smart grid is defined by the system ability to prevent the cascading failure or mitigate the failures of the system. The solution to this problem is presented by using an online coordinated asset like the smart transformer. In this case, the smart transformer is mentioned as a phase shifting transformer connected at a specific location and it is connected in series with the line impedance. This paper presents an analytical expression that links the power flow and the phase shift transformer in a radial standard power system (IEEE 33- and IEEE 69-bus system) as a case study.

The paper is organized as follows:

- Section 2 discusses the applied power flow and minor modification to building the load flow, and its application to a Pi-model.
- Section 3 investigates the mathematical model for smart transformer coordination.
- Section 4 presents standard distribution systems that are IEEE 33- and IEEE 69-bus systems as a case study for studying the impact of the smart transformer on a radial distribution system.

- Section 5 investigates the obtained results and discusses the proposed solution on different standard networks.
- Section 6 presents the conclusion of the paper and the recommendation for the future work.

2. Modified power flow

The proposed method in this paper is based on a direct approach power flow. The direct approach technique is the modifications implemented to the backward/forward power flow as presented in [9]. This is an especially designed technique for radial networks, inspired by well-known backward-forward sweep methods such as, for example, Ladder Iterative Technique, presented in [10]. Also, the modified load flow is known as the direct approach method according to [9]. This approach is applied to a balanced network, transformers, lines and the all are modeled as the series impedance Z_{ik} , and the equivalent injected bus current I_g , is calculated from:

$$I_g = \frac{P_i - jQ_i}{\text{conj}(V_i)}, \quad (1)$$

where $P_i - jQ_i$ is the power at each bus and V_i is the voltage at each bus. As already mentioned, the grid is a radial network so the branch current can be obtained by the following equation:

$$I_{\text{branch}} = BIBC \times I_g, \quad (2)$$

where $BIBC$ is the bus injection to the branch current matrix. This matrix is upper triangular and includes entry values of 1 and 0 only. The value is to be 1 if the current at the node i is connected to branch current I_{branch} as shown in Fig. 1. Otherwise, the value is to be 0. The voltage can finally be calculated as:

$$\Delta V = BCBV \times I_{\text{branch}}, \quad (3)$$

where ΔV is the voltage vector of the slack bus referred to the buses voltage, and $BCBV$ is the branch current to the bus voltage matrix. The bus voltage could be obtained by the following:

$$Vb = V_S - \Delta V, \quad (4)$$

where V_S is the voltage vector with the slack bus voltage at each entry.

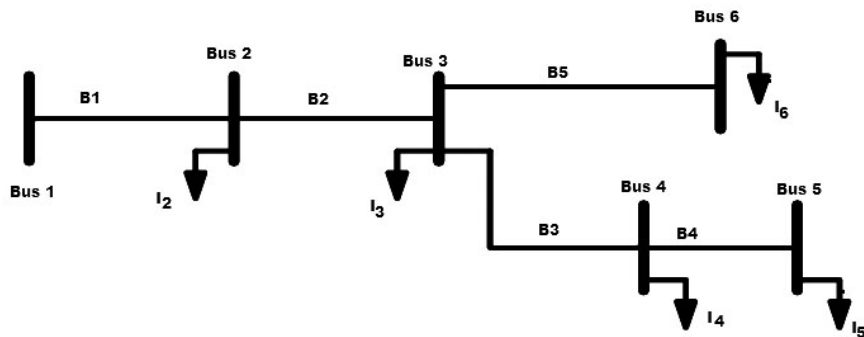


Fig. 1. Simple distribution system

When the system contains loops, no effect will happen to the current injections, but the newly added branches need to be included to the system. As shown in Fig. 2, a simple case is presented, it has only one loop. The new branches should be taken into consideration, so the injected current at bus 5 and bus 6 will be calculated as follows:

$$I'_5 = I_5 + I_{\text{branch}(6)}, \quad (5)$$

$$I'_6 = I_6 - I_{\text{branch}(6)}. \quad (6)$$

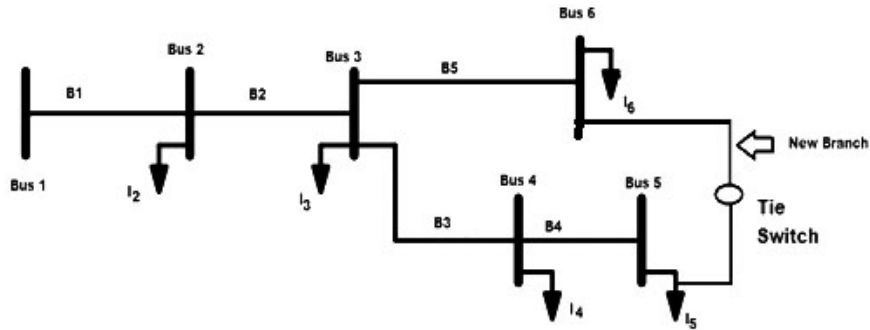


Fig. 2. Simple distribution system with one loop

The *BIBC* matrix can be presented as follows:

$$\begin{bmatrix} I_{\text{branch}(1)} \\ I_{\text{branch}(2)} \\ I_{\text{branch}(3)} \\ I_{\text{branch}(4)} \\ I_{\text{branch}(5)} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 + I_{\text{branch}(6)} \\ I_6 - I_{\text{branch}(6)} \end{bmatrix}, \quad (7)$$

where the modified *BIBC* matrix can be written as follows:

$$\begin{bmatrix} I_{\text{branch}(1)} \\ I_{\text{branch}(2)} \\ I_{\text{branch}(3)} \\ I_{\text{branch}(4)} \\ I_{\text{branch}(5)} \\ I_{\text{branch}(6)} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \\ I_{\text{branch}(6)} \end{bmatrix}, \quad (8)$$

The general formula from the modified *BIBC* matrix can be written as follows:

$$\begin{bmatrix} I_{\text{branch}} \\ I_{\text{branch}(\text{New})} \end{bmatrix} = [BIBC] \begin{bmatrix} I \\ I_{\text{branch}(\text{New})} \end{bmatrix}, \quad (9)$$

Regarding the voltage, the *BCBV* matrix has been created as in the base case. However, calculating the KVL for the network considers adding the new row for each loop in the grid.

The impedances included in the entries of the new rows of the matrix are marked positive or negative based on the reference of the current at various branches [9]. The general formula for the modified $BCBV$ is:

$$\begin{bmatrix} \Delta V \\ 0 \end{bmatrix} = [BCBV] \begin{bmatrix} I \\ I_{\text{branch(New)}} \end{bmatrix}, \quad (10)$$

where the system includes the Pi-equivalent model as shown in Fig. 3, the lines and the transformer are modeled by series impedances in the balanced systems. This model is acceptable for the short lines and the transformer that requires a small modification of the model to be appropriate to deal with the other devices.

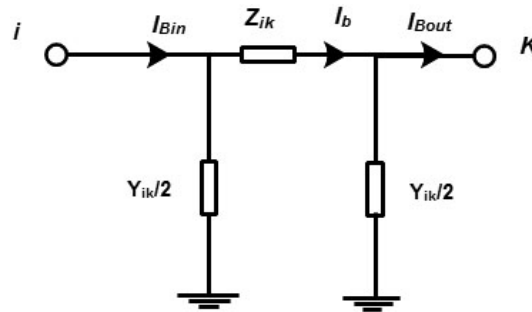


Fig. 3. Pi-equivalent model

The Pi-equivalent model is a medium length line that consists of the series impedance Z_{ik} , and the shunt admittance Y_{ik} , which should be included in the load flow calculation, where I_{Bin} and I_{Bout} are sending and receiving currents, respectively. That, due to changes in the calculation in the current injection vector, is to be:

$$I' = I_g + Y_B o V, \quad (11)$$

where Y_B is the bus admittance vector and o is the Hadamard product and V is the voltage vector. The sending current could be calculated and obtained as follows:

$$I_{Bin} = I_{\text{branch}} + \frac{Y_{ik}}{2} V_i. \quad (12)$$

The receiving current can be calculated through:

$$I_{Bout} = I_{\text{branch}} - \frac{Y_{ik}}{2} V_k. \quad (13)$$

3. Smart transformer model

The smart transformer can be represented by an equivalent circuit as shown in Fig. 4 and Fig. 5 which is valid to model the smart transformer based on the turn ratio of the transformer. The turns ratio a is a complex number and could be calculated as: $a = |a| e^{j\theta}$, where $|a|$ is

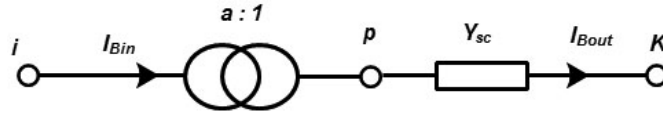


Fig. 4. Equivalent model of the smart transformer

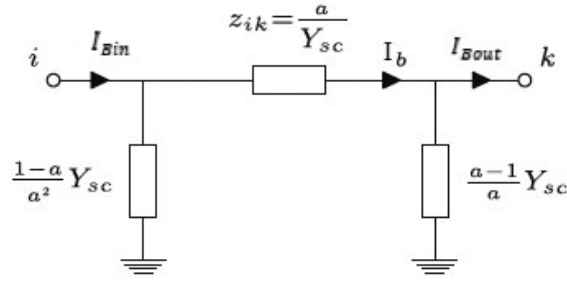


Fig. 5. Pi-equivalent model of the smart transformer

the regulation between the primary and the secondary voltage magnitude and θ is the phase shift angle of the transformer.

The transformer fundamental equation can be expressed as the following, to show the relation between the voltages of both sides primary and secondary.

$$V_i = aV_p = a \left(\frac{I_{Bout}}{Y_{SC}} + V_k \right), \quad (14)$$

$$I_{Bout} = \hat{a}I_{Bin}, \quad (15)$$

where \hat{a} is the complex conjugate of the turn ratio.

Applying the nodal analysis to the phase shift transformer that can be derived from Equations (14) and (15) proves the symmetry of the admittance matrix as follows:

$$I_{Bin} = \frac{1}{\hat{a}a}Y_{SC}V_i - \frac{1}{\hat{a}}Y_{SC}V_k, \quad (16)$$

$$-I_{Bout} = -\frac{1}{a}Y_{SC}V_i + Y_{SC}V_k. \quad (17)$$

The appropriate equivalent of the smart transformer must uphold the structure of Equation (3) to comply with the modified load flow as:

$$V_i - V_k = \frac{a}{Y_{SC}} \left(I_{Bout} + \frac{a-1}{a}Y_{SC}V_k \right) = \frac{a}{Y_{SC}} I_{branch}, \quad (18)$$

where I_{branch} is defined as follows:

$$I_{branch} = I_{Bout} + \frac{a-1}{a}Y_{SC}V_k. \quad (19)$$

The input current to the transformer can be expressed as:

$$I_{Bin} = e^{j2\theta} I_{Bout} + \frac{1-a}{|a|^2} Y_{SC} V_k . \quad (20)$$

The last three Equations (18)–(20) represent the equivalent circuit of the smart transformer, which is represented in Fig. 6. The smart transformer equivalent circuit is not a clear pseudo Pi-equivalent model, but it is appropriate for the modified power flow [11].

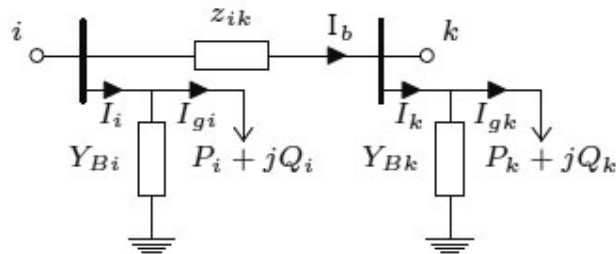


Fig. 6. Pseudo Pi-equivalent model of the smart transformer

4. Standard distribution system

The direct power flow approach is applied in the IEEE 69-bus network, which is shown in Fig. 7. The IEEE 69-bus system has 69 nodes, 73 branches, 5 loop switches and the total load (3802.2 + j2694.6) kVA with a base voltage magnitude that is equal to 12.66 kV and base-apparent power that is equals to 100 MVA, Bus “1” is considered to be a slack-bus [12].

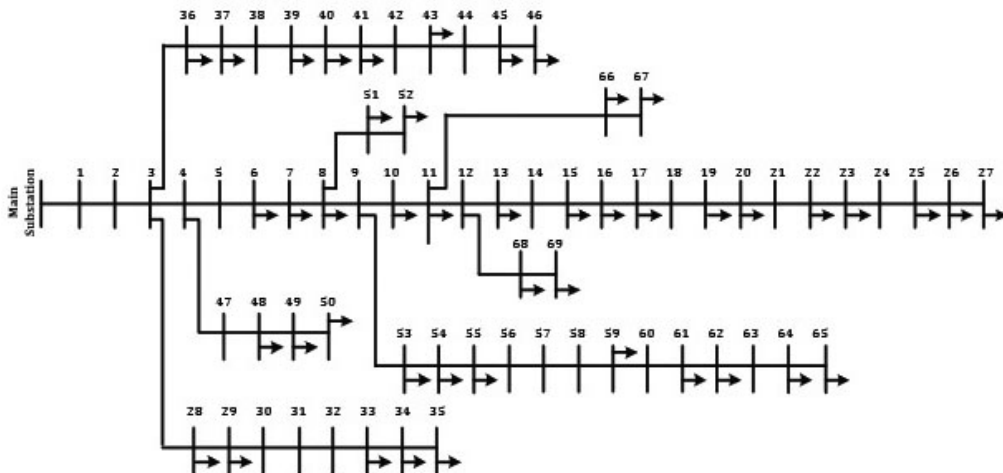


Fig. 7. Single line diagram of IEEE 69-bus network

Also, the modified IEEE 33-bus radial distribution system is applied in this contribution to test the effectiveness of the smart transformer and its contribution in minimizing the power losses in addition to enhancing the voltage profile of the system. The IEEE 33-bus system consists of 33 buses and 32 lines, also the distribution network contains five tie switches, as shown in Fig. 8. The mentioned distribution system has a base voltage of 12.66 kV, a load size of 3.715 MW and 2.3 MVar. All the details about the distribution system including the line impedance and active and reactive power are mentioned in [13, 14].

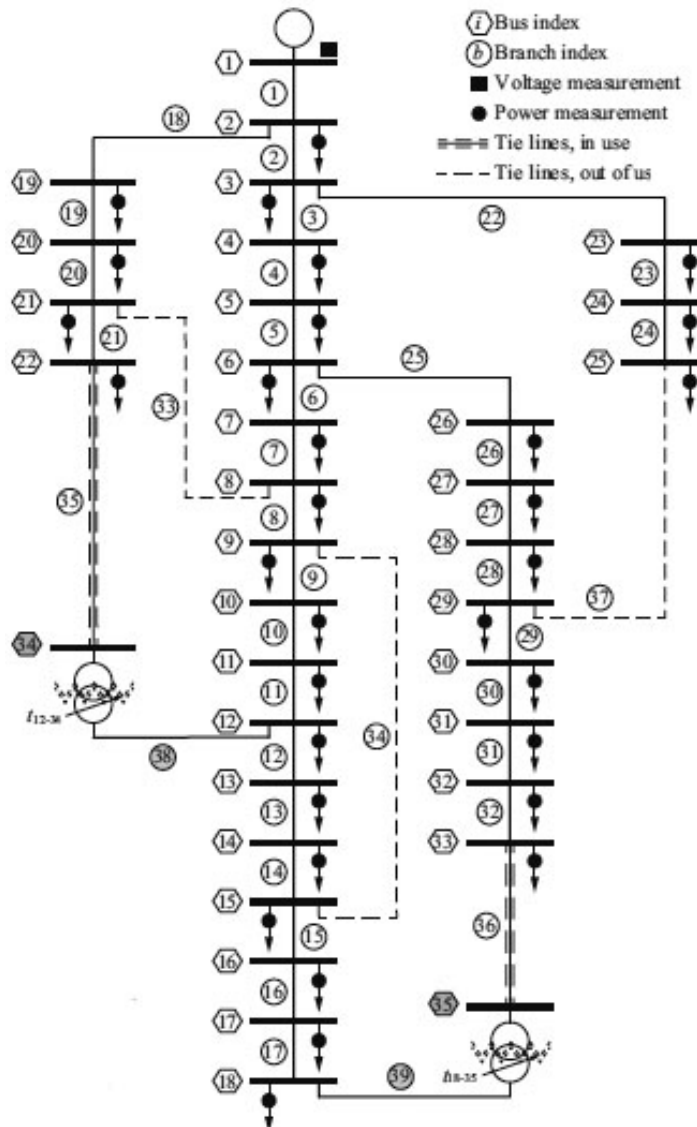


Fig. 8. IEEE 33-bus radial distribution system

Two transformers will be connected to the system using two existing tie lines to mesh the distribution network by means of the smart transformer. The data of the transformer is presented in the following Table 1.

Table 1. Smart transformer data

Transformer	Transformer 1	Transformer 2
S (KVA)	250	400
R_{Sc} (%)	0.95	0.95
X_{Sc} (%)	4.80	4.80
a (pu)	1.00	1.00
θ	5	-3

5. Results and discussion

The results obtained for the IEEE 33- and IEEE 69-bus distribution systems are shown in Table 2. It can be observed that the results for the base case (without smart transformer), with the total power loss of both systems, are 211 and 224 kW respectively. The results for the load flow obtained from the standard case were based on the direct load flow approach method. The results show that the total power losses in the IEEE 33-bus system for both active and reactive power are 211 kW and 178 kvar, respectively. There, the minimum node voltage is 0.88 V(pu), while the active power losses are 224 kW and the reactive loss for the IEEE 69-bus distribution system is 182 kvar. The minimum voltage node is 0.87 V(pu).

Table 2. Smart transformer results

System	P loss	Q loss	Min voltage	No. of transformer	Location of T1 and T2
IEEE 33	174	166	0.925	2	T1: 12 and 34 T2: 18 and 35
IEEE 69	187	176	0.9188	2	T1: 27 and 70 T2: 18 and 35

Based on the following results, installing the smart transformer is helps reduce the power losses and enhances the voltage profile. Installing the smart transformer in series with the line impedance makes it an issue as to where is the optimum position for installing the smart transformer. The code is adapted to select the transformer location based on selecting two different locations to install the transformer as it is proposed using only two transformers for these networks. Also, the program calculated all possible locations to install the smart transformer and for example for the IEEE 33-bus system, it found that there are 436 possible positions for installing the transformer. The program selects only one possible answer, where minimum losses are achieved. Table 2 shows the main output results of the program which reflect the smart transformer's impact on minimizing power losses.

For the results of the IEEE 33-bus system, the program selected a certain position of the smart transformer to be located between:

- The first transformer is located between bus 12 and bus 34.
- The second transformer is located between bus 18 and bus 35.

The positions of the smart transformer are selected based on minimizing the power loss P_{loss} which is decreased to be 174 kW while the reactive power loss Q_{loss} is also decreased to be 166 kvar. In addition, the voltage profile of the system is enhanced, and the minimum voltage node is 0.925 V(pu).

For the results of the IEEE 69-bus system, the program selected a certain position of the smart transformer to be located between:

- First transformer is located between bus 27 and bus 70.
- Second transformer is located between bus 50 and bus 71.

Using the smart transformer contributed to decreasing the power loss to 187 kW for the active power loss and the minimum voltage node is 0.9188 V(pu) which indicates the voltage profile enhancement.

Fig. 9 shows the obtained voltage profile of the IEEE 33-bus in the standard case for the power flow which is running without installing the smart transformer based on the direct approach load flow. The case depends on calculating the voltage at each bus and the curve shows the magnitude of the voltage at each corresponding bus. The results show a minimum of approximately 0.88 V(pu). Fig. 10 shows the voltage profile of the system with the installed smart transformer; the figure proves the enhancement in the voltage profile of the network as the result of installing the transformer. The minimum voltage node is calculated to be 0.925 V(pu).

Fig. 11 shows the voltage profile of the IEEE 69-bus system with the installed smart transformer; the figure proves the enhancement in the voltage profile of the network as a result of

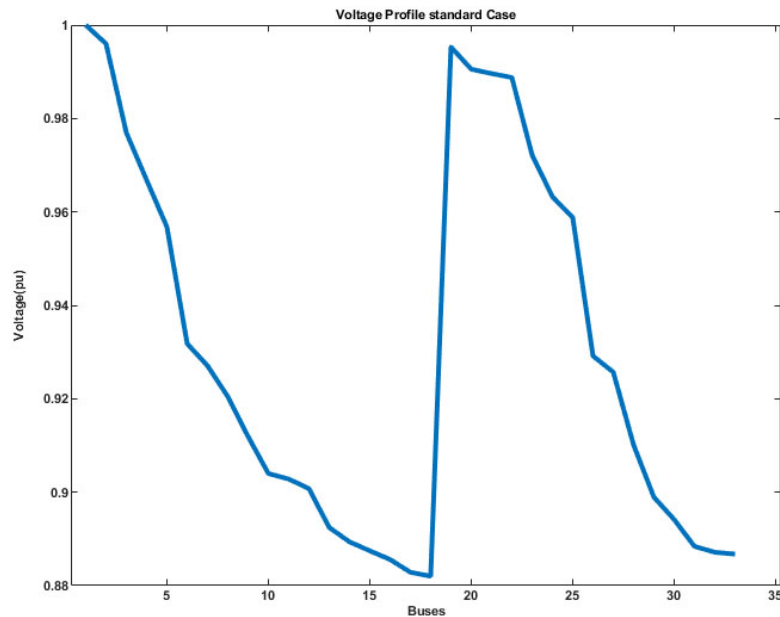


Fig. 9. Voltage profile without transformer for the IEEE 33-bus system

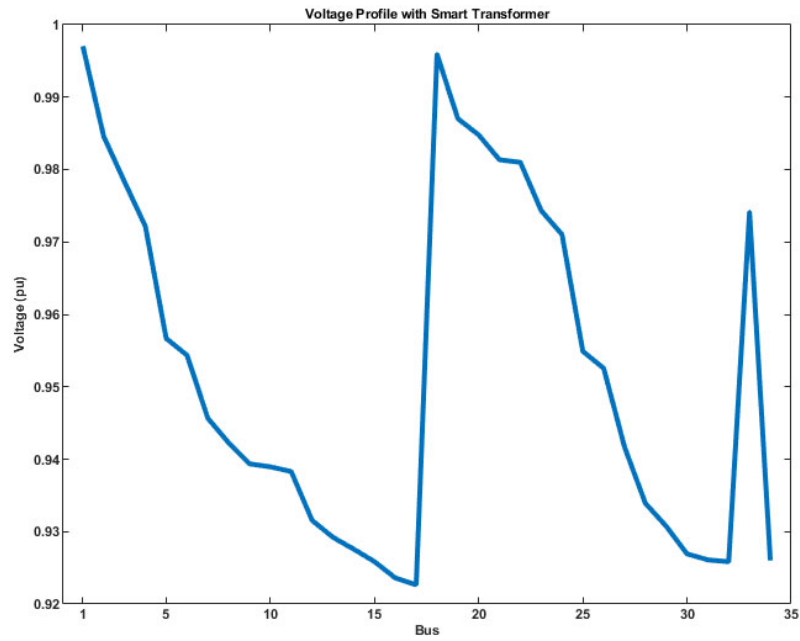


Fig. 10. Voltage profile with smart transformer for IEEE 33-bus system

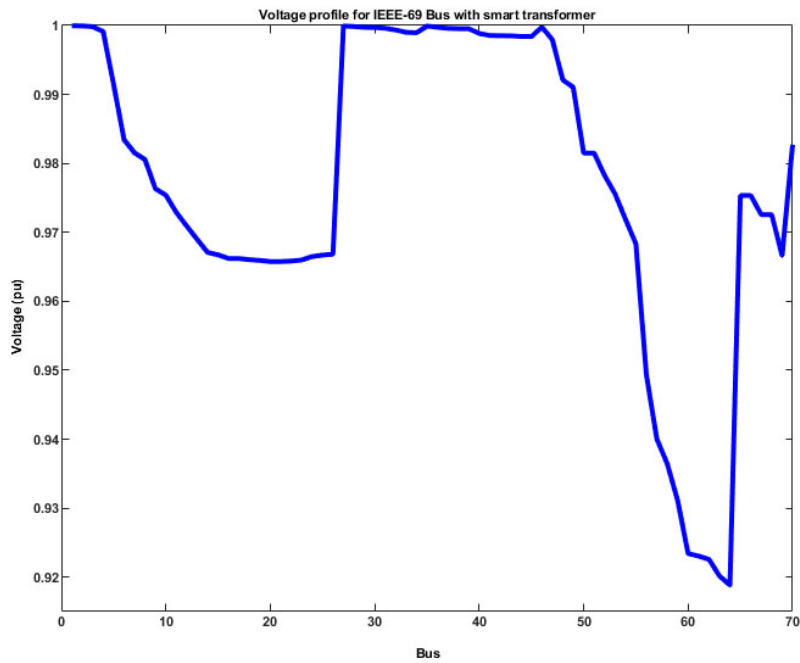


Fig. 11. Voltage profile with smart transformer for IEEE 69-bus system

installing the transformer. The minimum voltage node is calculated to be 0.9188 V(pu) while in the standard case for this network the minimum voltage node is 0.87 V(pu).

6. Conclusions

This paper presents a novel technique for calculation the power flow in weekly meshed networks. The paper proposes the employment of the direct power flow approach to different radial power distribution networks to utilize the grid components. The utilization of smart transformer and Pi-equivalent models for the network lines is investigated in detail in this paper. The smart transformer is connected in series with the line impedance. Because of the inherent asymmetry of the admittance matrix of the smart transformer, the implementation of the direct load flow approach, which is a minor modification and brings visible results, is a real asset. The technique is employed in various standard radial systems to assess the superiority and the excellence of the technique to solve problems of common networks with the utilization of the smart transformer. The results have proved that using the smart transformer enhances the voltage profile of the network and reduces the power losses.

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