

Smart transformer impact on a radial distribution system

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Abstract

The work is intended to extend the application of 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 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. Solution of the smart transformer using the direct approach power flow method is quite straightforward. This model is applied on a radial distribution system which is the IEEE-33 bus system as a case study. Also, the paper optimizes the best allocation of the smart transformer to reduce the power losses of the grid.

Keywords: 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 electric vehicle (EV) and its charging stations may cause some of operational and technical challenges for the distribution systems [1]. That refers to their prices which supported by attractive fees I addition helpful promotion policies. Based on the mentioned aperients the end stakeholders are diverged to be not only electricity consumers but also in different cases producers. The genuine distribution network restricts wide utilization of renewable energy resources, provide 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 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 present solutions and capabilities like an active filter, flexible ac transmission systems (FACTS), DC high-voltage, electronic breakers and solid-state transformers, [2]. Now the applicability to deliver a high voltage and current with low losses, done through the recent generation of semiconductor devices based on silicon material.

From the power system side, the utilizations of the power electronics solutions, the updated technologies permit widely control of the power flow at different conditions, moreover these components contribute in making it applicable to implement widely discussed smart grids which execute information and communication technology (ICT) to distribution network operation and planning [3]. Based on power electronics, the smart transformer (ST) can play important role to utilize in multiple functions and introduce an ancillary service. The concept of smart transformer (ST) has been investigated for the first time with Project Highly Efficient and Reliable ST [4]. MIT in 2011 has selected the smart transformer as a one of the ten emerging technology breakthroughs which has a chance to create a great effect globally [5]. 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.

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Same time keeping the cost into account. In addition, the smart transformer can present some new solutions for the industry sector [6]. The smart transformer specifications and the availability of the DC links in the smart transformer can control different levels of harmonics, in addition supply different loads with DC or at variable frequencies [7].

Minimization 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 through using distributed generations as a solution for this problem. Distributed generation (DG) considers a solution for such problem, in addition the location of the DG enhances the voltage profile. That make the researchers in the last years focus on exploring other aspects of power system like reliability stability and protection.

In this paper, a model of smart transformer is introduced for self-repairable of smart grid. The self-healing of the smart grid is defined by the system ability to prevent the cascading failure or mitigating the failures of the system. The solution of this problem is presented by using the online coordinated asset like the smart transformer. In this case, the smart transformer is mentioned as a phase shifting transformer connected in a certain in series. This paper presents an analytical expression which link between the power flow in a radial standard power system (IEEE-33bus system) as a case study of the phase shift transformer

The paper is organized as the following:

- Part 2 discuss the applied power flow and the minor modification in building the load flow and its application on a PI-model.
- Part 3 investigates the mathematical model for the smart transformer coordination.
- Part 4 investigates the obtained results and discussion of the proposed solution on different standard networks. The last part,
- Part 5 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 modification which implemented to the backward/forward power flow as presented in [8]. This technique as known is valid for radial system, complete details about the backward/forward sweep method, Ladder iterative technique, is presented in [9]. Also, the modified load flow is known by the direct approach method according to [8]. This approach is applied on a balanced network, transformers, lines and the all are modeled as a series impedance (Z_{ik}), where the equivalent injected bus current (I_g), is calculated from:

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

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

$$I_{branch} = BIBC \cdot I_g \quad (2)$$

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

$$\Delta V = BCBV \cdot I_{branch} \quad (3)$$

Where the ΔV is a voltage vector of the slack bus referred to the buses voltage, and the ($BCBV$) is the branch current to the bus voltage matrix. Where the buss voltage could be obtained by the following:

$$Vb = V_s - \Delta V \quad (4)$$

Where the (V_S) is the voltage vector with the slack bus at each entry.

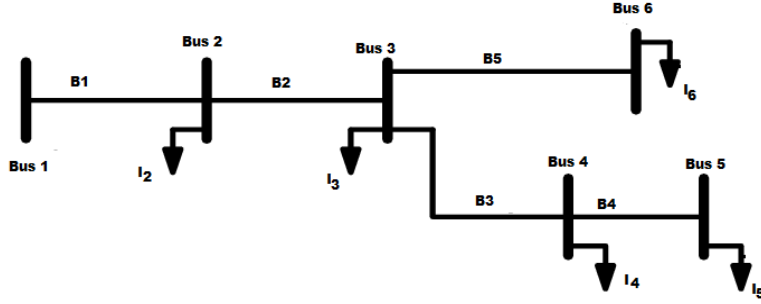


Fig. 1. Simple distribution system.

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 calculation of the injected current at bus 5 and bus 6 will calculate as following:

$$I_5' = I_5 + I_{branch(6)} \quad (5)$$

$$I_6' = I_6 - I_{branch(6)} \quad (6)$$

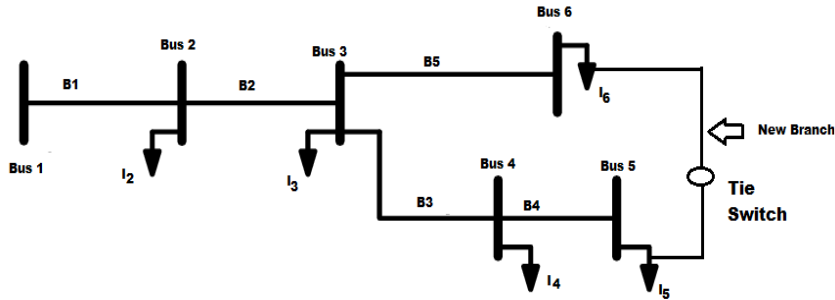


Fig. 2. Simple distribution system with one loop

The BBC matrix Can be presented as following

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

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

$$\begin{bmatrix} I_{branch} \\ I_{branch(New)} \end{bmatrix} = [BIBC] \begin{bmatrix} I \\ I_{branch(New)} \end{bmatrix} \quad (8)$$

Regarding the voltage the genal formula for the modified BCBV is:

$$\begin{bmatrix} \Delta V \\ 0 \end{bmatrix} = [BCBV] \begin{bmatrix} I \\ I_{branch(New)} \end{bmatrix} \quad (9)$$

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

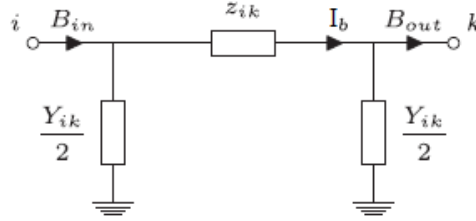


Fig. 3: Pi- Equivalent model

The Pi equivalent model consider a medium length lines consist of a series impedance (Z_{ik}), and a shunt admittance (Y_{ik}), which is could be including in the load flow calculation. That due to changing in calculation in the current injection vector to be

$$I' = I_g + Y_B o V \quad (10)$$

Where the (Y_B) is the bus admittance vector and (o) is the Hadmard product. The sending current could be calculated and obtained as following

$$I_{Bin} = I_{branch} + \frac{Y_{ik}}{2} V_i \quad (11)$$

The receiving current can be calculated through:

$$I_{Bout} = I_{branch} - \frac{Y_{ik}}{2} V_k \quad (12)$$

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 turns ratio of the transformer (a), is a complex number and could be calculates as: $a = |a|e^{j\theta}$, where ($|a|$) is the regulation between the primary and the secondary voltage magnitude and the (θ) is the phase shift angle of the transformer.

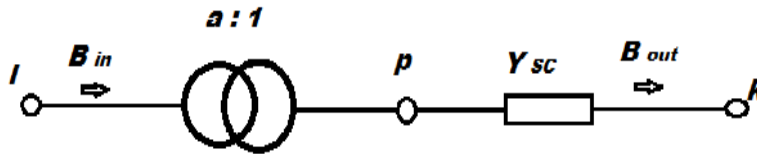


Fig. 4. Equivalent model of the smart transformer

The transformer fundamental equation can be expressed as the following t show the relation between the primary with the secondary side for the voltage

$$V_i = a V_p = a \left(\frac{I_{Bout}}{Y_{SC}} + V_k \right) \quad (13)$$

$$I_{Bout} = \hat{a} I_{Bin} \quad (14)$$

Where (\hat{a}) is the complex conjugate of the turns ratio.

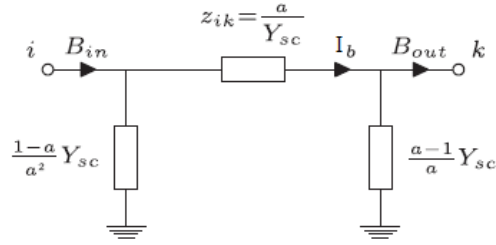


Fig. 5. Pi-equivalent model of the smart transformer.

Applying the nodal analysis on the phase shift transformer which can be derived from (13) and (14) which prove the symmetry of the admittance matrix as following:

$$I_{Bin} = \frac{1}{aa} Y_{sc} V_i - \frac{1}{a} Y_{sc} V_k \quad (15)$$

$$-I_{Bout} = -\frac{1}{a} Y_{sc} V_i + Y_{sc} V_k \quad (16)$$

Appropriate equivalent of the smart transformer must uphold the structure of equation (3) and to comply the modified load flow as:

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

Where I_{branch} is defined as following:

$$I_{branch} = I_{Bout} + \frac{a-1}{a} Y_{sc} V_k \quad (18)$$

The input current to the transformer can be expressed as:

$$I_{Bin} = e^{j2\theta} I_{Bout} + \frac{1-a}{|a|^2} Y_{sc} V_k \quad (19)$$

The last three equations (17) – (19) represent the equivalent circuit of the smart transformer which is represented in Fig.6 the equivalent circuit is not a clear Pseudo Pi-equivalent model but it is appropriate for the modified power flow.

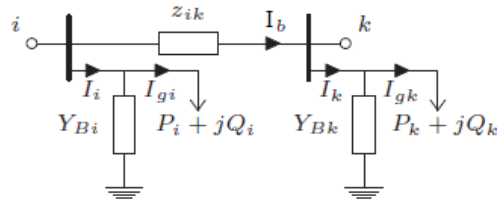


Fig. 6. Pseudo Pi-equivalent model of the smart transformer

4. Standard Distribution System

The modified IEEE 33-Bus radial distribution system which is applied in this contribution to test the effectiveness of the smart transformer and its contribution in minimizing the power losses in addition enhancing the voltage profile of the system. The IEEE-33 bus system consists of 33 buses and 32 lines, 5 tie lines and has a voltage of 12.66 kV, in addition the load size of 3.715 MW and 2.3 MVar. all the details about the distribution system including the line impedance the power being active and reactive power is mentioned in [10-11].

In the system, two transformers will be connected to then system use two existing tie line to mesh the distribution network by using the smart transformer. the data of the transformer is mention in the following table:

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

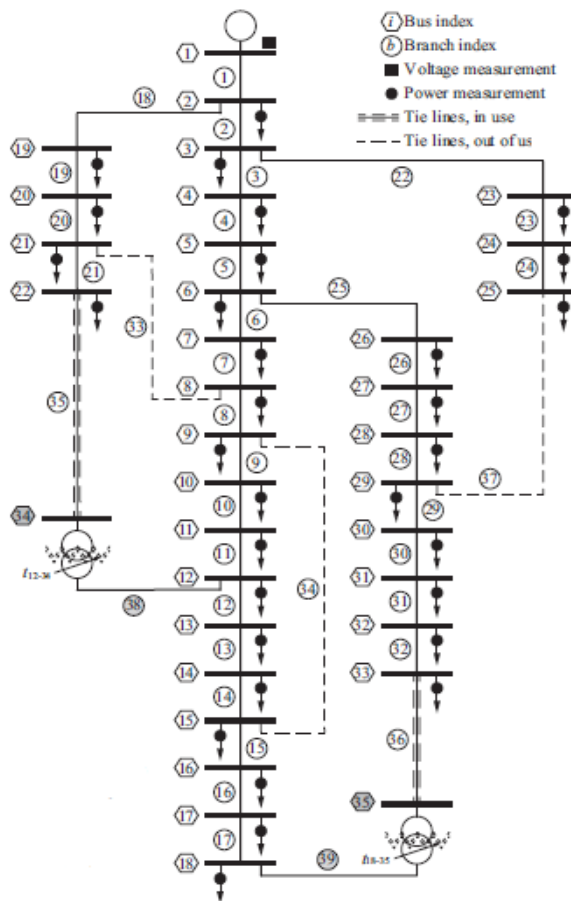


Fig. 7. IEEE-33 bus radial distribution system

5. Results and Discussion

The results obtained for the 33-Bus distribution system are shown in Table 1. It can be observed that for the base For base case (without smart transformer), the total power loss of the system is 272.998 kW. The results based on the standard case for the load flow based on the direct approach load flow method.

The results shows that the total power losses of being active or reactive power is being 211 KW and 178 KVAR. Where the minimum node for Voltage is being 0.88 V(pu).

Based on the following results installing smart transformer is being a helper for enhancing the power losses and also enhancing the voltage profile. installing the smart transformer in series with the line impedance make it an issue as where the optimum position for installing the smart transformer. the code is adapted to select the transformer location based on selecting two different location to install the transformer the system is calculated the all possible locations to inject the transformer and calculate 436 possible position for installation and select only one possible answer based on the losses. Table show the main output results from the system the total power losses of the system when the smart transformers are installed. The system selected a certain position of the smart transformer to be located between:

- First transformer is located between bus 12 and bus 34.
- Second transformer is located between bus 18 and bus 35.

The positions of the smart transformer is selected based on minimizing the power losses (Ploss) which is decreased to be 174 KW while the reactive power losses (Qloss) also decreased to be 176 KVAR. In addition the voltage profile of the system is enhanced and the minimum voltage node is being 0.925 V(pu).

Table 2. Smart transformer result

Ploss	Qloss	Min voltage	No. of transformer	Location of T1 and T2
174	178	0.925	2	T1: 12 and 34 T2: 18 and 35

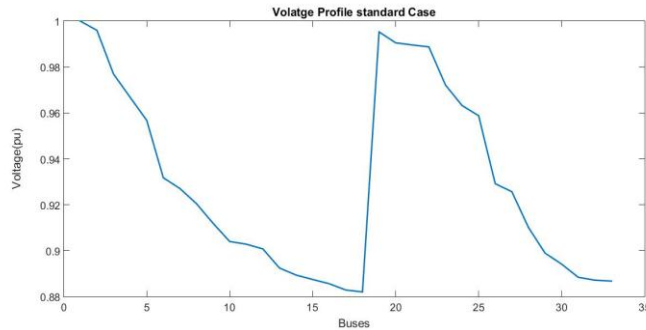


Fig. 8. Voltage profile without transformer

Fig. 8 shows the obtained voltage profile 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 is depending on calculating the voltage at each bus and the curve shows the magnitude of the voltage at each corresponding bus. The results show the minimum is approximately 0.88 V (pu). Fig. 9 shows the voltage profile of the system with 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).

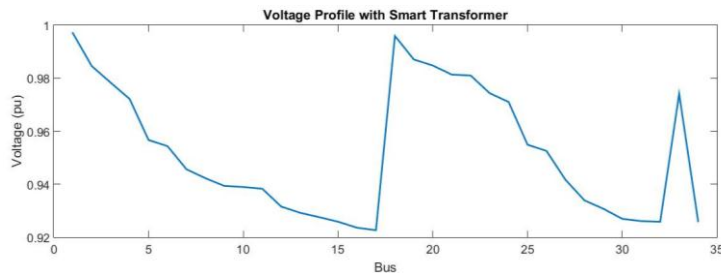


Fig. 9. Voltage profile with smart transformer

6. Conclusion

This paper proposes the employment of the direct approach power flow to radial power distribution network to utilize the grid components. The embodiment 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, thus, asset of minor modifications is implemented at the direct approach load flow particularly on the BIBC matrix and BCBV matrix. The technique is employed on a standard radial which is the IEEE-33 bus system to assess the superiority and the excellence of the technique to solve the common networks with the embodiment of smart transformer. the results are proved that and the enhancement of the power system using the smart transformer as the power losses is reduced and the voltage profile is enhanced.

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