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An Overcurrent Protection Relay Based on Local Measurements

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***Abstract*—Power grid overcurrent relays are used to protect the interphase faults as well as single-phase-to-ground faults. However, these relays do not guarantee protection due to the rapid increasing short circuits which may be the consequence of demanding more and more power usage by the commercial and residential users. In this paper, a method is presented to improve the functionality of the overcurrent relay. This method is based on locally accessible measurements. It does not require any online-information and communication facilities regarding varying short-circuit levels caused by distributed energy resources infeeds. This method is adaptive and uses a least square algorithm to determine the Thevenin circuit equivalent using local measurements. The proposed method is evaluated and the results indicate that the Thevenin equivalent based method provides an improvement to the relays tripping time.**

***Index Terms*—Impedance plane, least error square, local measurement, overcurrent relay.**

I. INTRODUCTION

Overcurrent relays are widely used for the protection of transmission and distribution networks. The increasing utilization of distributed generations (DGs) in distribution networks lead to a challenge for the conventional relays, due to the varying short circuit levels and load profile. Analysis can be conducted via an adaptive Thevenin circuit equivalent in both fault and normal conditions. The circuit equivalent variation affects the time-overcurrent relay characteristics, i.e., tripping time and pick-up parameters [1]- [3]. The distance protection can overcome this issue. Indeed, the tripping and pick up parameters do not change in the impedance plane and are independent of the feeding Thevenin equivalent impedance in this protection. Improving and upgrading the distance protection requires replacement of the existing overcurrent protection. These replacements are expensive and are not economic.

This paper proposes an algorithm for overcurrent protection that does not require hardware replacement or alteration. In this algorithm, only local measurements are used to develop overcurrent protection. The proposed algorithm can keep a constant for overcurrent protection independent of impedance variation.

II. FUNDAMENTAL PRINCIPLE DEVELOPMENT

A. R-X Impedance Plane

To investigate the effect of the Thevenin circuit equivalent on the overcurrent protection the relation $I_S \geq I_P$ is used. I_S and I_P are short circuit level and pick up currents, respectively. It means if the measured short circuit current is greater than the pick up current, the overcurrent relay starts to operate.

In the proposed algorithm, the tripping and pick up criteria are transformed into the impedance plane. This transformation depends on the Thevenin circuit equivalent parameters. The positive sequence parameters for a three phase fault are shown in Fig. 1. E_T, Z_T, Z_S, I_S, and V_S are Thevenin equivalent voltage source, equivalent impedance, short circuit impedance, current and voltage at the relay point, respectively. In calculations, E_T is considered as the reference in per unit (p.u.), $E_T = 1\angle 0pu$. From Fig. 1,

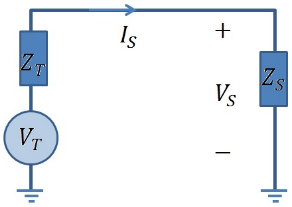

Fig. 1. Thevenin circuit equivalent, three phase fault

$$I_S = \frac{E_T}{Z_S + Z_T} \tag{1}$$

According to the operation constraint for the overcurrent relay,

$$\frac{1}{I_P} \geq |Z_S + Z_T| \tag{2}$$

Eq. (2) represents the tripping and pick up criteria which are transformed into the impedance plane. This equation could be written in the complex plane,

$$|Z - Z_\circ|^2 = (\frac{1}{I_P})^2 \tag{3}$$

where Z and $Z_\circ$ are impedance on the circle and circle center, respectively. From (2) and (3) it is concluded that the overcurrent characteristic represents a circle with center $-Z_T$ and radius $\frac{1}{I_P}$. Changing the Thevenin parameters, Z_T and V_T $(1pu)$, change the center and radius of the circle in both increasing and decreasing directions.

B. Proposed Algorithm

In conventional power systems the pick up current in overcurrent protection is usually considered a fix value. The fixed value for the pick up current is equivalent with a fixed impedance plane characteristic. This characteristic is not fix in the smart power systems with distributed energy resources. Therefore, the impedance characteristic or Thevenin equivalent should vary according to the power system variations.

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The behavior of the pick up current when Thevenin equivalent parameters change is shown in Fig. 2. The Thevenin impedance is shown by the center of the circle $Z_\circ$. Changing V_T and Z_T change the radius to r' and circle center to $Z'_\circ$. Therefore, the radius of the overcurrent characteristic is adapted by I_P. The new circle has the radius of r' and the center of $Z'_\circ$. Assume $real\{Z'_\circ\} = X'_\circ$ and $imag\{Z'_\circ\} = Y'_\circ$. Since $r' = \frac{1}{I'_p}$, the pick up current is obtained,

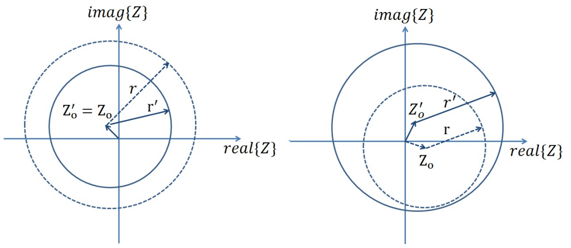

Fig. 2. Adaptation of the overcurrent characteristic

$$I'_p = \frac{1}{\sqrt{(X - X'_\circ)^2 + (Y - Y'_\circ)^2}} \quad (4)$$

If we consider the Thevenin equivalent voltage source as E_T, the equation 4 could be rewrite as,

$$I'_p = \frac{E_T}{\sqrt{(X - X'_\circ)^2 + (Y - Y'_\circ)^2}} \quad (5)$$

Therefore, by measuring the Thevenin equivalent voltage and impedance the pick up current (I'_p) is computed as below.

In Fig. 1 I_S and V_S are known. The state equation of the circuit simply obtained,

$$E_T - Z_T I_S = V_S \quad (6)$$

If we consider $V_S = V_S^r + jV_S^i$, $I_S = I_S^r + jI_S^i$, $Z_T = R_T + jX_T$ and $S_T = E_T^r + jE_T^i$ two different equations in imaginary and real parts will be derived from (6),

$$\begin{aligned} -R_T I_S^r + X_T I_S^i + E_T^r &= V_S^r \\ -R_T I_S^i - X_T I_S^r + E_T^i &= V_S^i \end{aligned} \quad (7)$$

This linear set equations can be viewed as a matrix equation $AX = B$, which $X = [R_T\ X_T\ E_T^r\ E_T^i]^T$, $B = [V_S^r\ V_S^i]^T$ and A is the coefficients matrix of variables X (observation matrix).

$$AX = B \quad (8)$$

$$\begin{pmatrix} -I_S^r & I_S^i & 1 & 0 \\ -I_S^i & -I_S^r & 0 & 1 \end{pmatrix} \begin{pmatrix} R_T \\ X_T \\ E_T^r \\ E_T^i \end{pmatrix} = \begin{pmatrix} V_S^r \\ V_S^i \end{pmatrix}$$

Solving this equation gives the unknown variables which are real and imaginary parts of the equivalent Thevenin voltage and impedance.

Since in general, matrix $[A]_{m\times n}$ is not a square matrix, (8) has a solution as below,

$$\begin{cases} X = A_L^{-1} B \\ A_L^{-1} = (A^T A)^{-1} A^T \end{cases}, \text{ If A has full column rank } n$$

$$\begin{cases} X = A_R^{-1} B \\ A_R^{-1} = A^T (A^T A)^{-1} \end{cases}, \text{ If A has full row rank } n \quad (9)$$

where A_L and A_R are the left and right inverses, respectively. The least squares method is used to estimate the equivalent Thevenin voltage and impedance parameters in (9) [4]- [7]. The least square method is valid for a constant vector X. However, in this case the voltage and impedance parameters are not constant. This is due to several factors such as distributed energy resources, which are not connected to the power network continuously, topology of the network, load parameters, which vary and are nonlinear, etc. The variation of these parameters is stepwise in a time duration, but these parameters are constant on the different step levels for a certain period of time.

C. The Impact of Energy Resources on the Thevenin equivalent

A power system shown in Fig. 3 is considered to study the Thevenin equivalent changing in successive simulations via load flow recalculations in steady state. This power system has been modeled via MATLAB. The modeled power system consists of a wind generator including twelve windmills at total power of $25MVA$, a three winding power transformer $(230/63/20kV)$, a two winding power transformer $(11/20kV)$, three $20kV$ lines, and two $60MW$, $20kV$ loads. The lines are protected by overcurrent relays at the beginning of each line. This modeled power system is connected to the national network and a medium voltage grid.

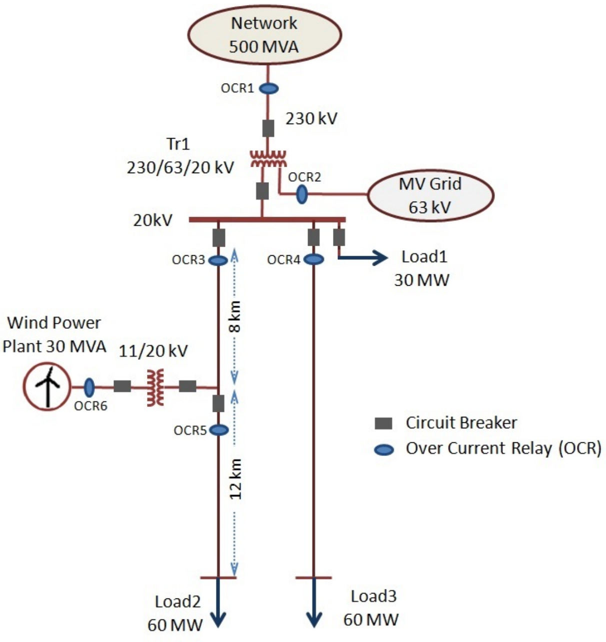

Fig. 3. Power system model for analysis the Thevenin equivalent

The modeled wind park generates power during 24 hours. To consider the calm wind condition it generates power between 2:00 p.m. and 5:00 p.m., and the windmills are disconnected from the grid one by one. To study the Thevenin

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equivalent variation another case is considered. In this case we considered the generated power by the wind park between 6:00 a.m. and 4 p.m., when two generators were disconnected while other ones continuously working.

The Thevenin equivalent is varying due to the changing the number of wind parks that are connected to the grid. The Thevenin equivalent impedance and voltages are shown in Fig. 4 and 5 for the overcurrent relay 5 (OCR5). As it can be seen from these figures, changing the number of working wind parks causes a change in the Thevenin equivalent values. Switching off each of the wind parks causes the impedance and voltages change 0.06Ω and $1.5kV$, respectively.

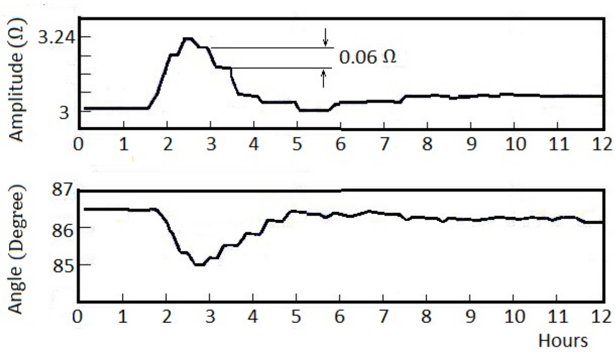

Fig. 4. Measured impedance by the OCR4

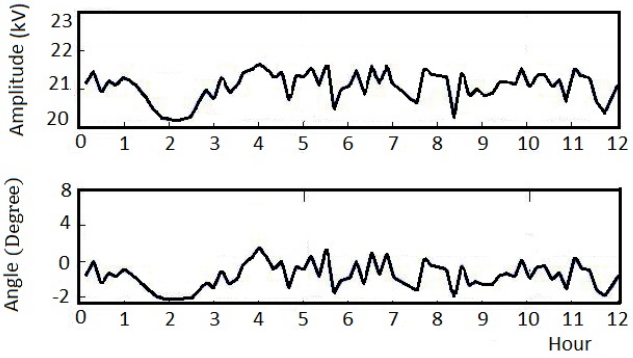

Fig. 5. Thevenin equivalent voltage at the OCR4 location

III. SIMULATION RESULTS

The proposed method is evaluated using MATLAB/SUMULINK. Fig. 6 shows the power system model. In this grid the two energy resources are used and connected to the grid one by one. At the beginning of simulation one of the energy resources is already connected to the grid and after a period of time the second source is connected. A two phase to ground fault has been considered next to the seventh overcurrent relay (OCR7). All of the relays estimate the Thevenin equivalent by the least squares method.

To evaluate the proposed method OCR6 and OCR7 relays are under investigation in the $5km$ line. These relays are coordinated according to their time-current characteristics. The pick up current for the OCR7 relay is considered as $1.8kA$ with tripping time $0.12s$. The OCR6 relay is a back up for the OCR7 relay. It means if the OCR7 relay does not operate, then OCR6 relay will operate. The pick up current and tripping time for the OCR6 relay are $1.8kA$ and $0.45s$, respectively.

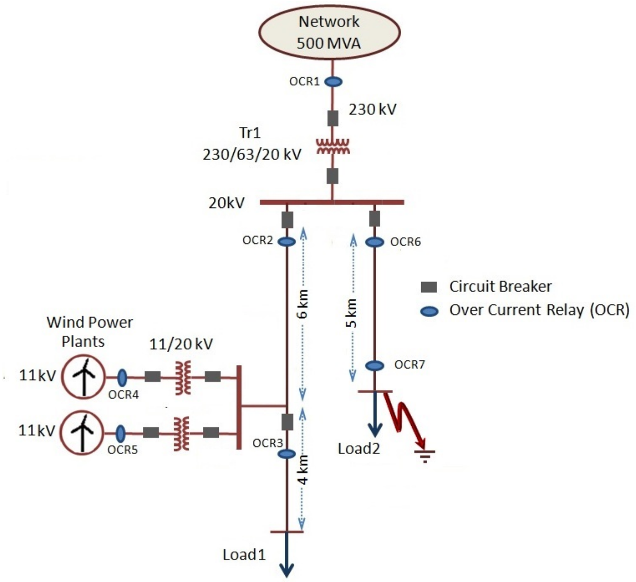

Fig. 6. Power system model with two distributed energy resources

To clear the fault in minimum time the OCR6 relay provides a high set element. The highest short circuit current pertains to the symmetric three phase short circuit. Therefore, the highest set element is considered for the OCR6 relay. Three phase short circuit current at 85% of the line is $3.8kA$. Therefore, the pick up current for the high set element was considered as $3.5kA$.

The proposed algorithm is required when the number of energy resources are changed. Fig. 7 shows the impedance characteristic for both OCR6 and OCR7 relays. As it can be seen, before second energy resource connects to the grid the, center of OCR6 relay was in the origin. When this energy resource connects to the grid, the center has been shifted from the origin to a Thevenin impedance. As it was mentioned earlier, a higher pick up current exhibits a smaller radius. Fig. 7 indicates that for the OCR6, the circle radius with the tripping time $Trip_{time} = 0.08s$ (solid circle) is smaller than that one with the $Trip_{time} = 0.45s$ (dash circle).

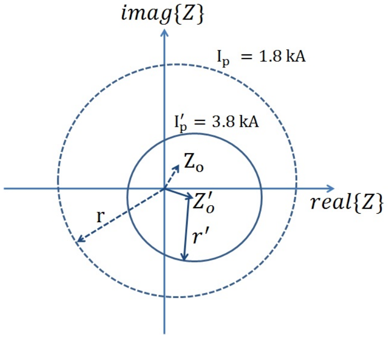

Fig. 7. Pick up current transformation into the impedance plane

Let consider a three phase to ground fault at the OCR7 relay

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location. In this fault, the measured impedance by OCR7 relay is zero and by OCR6 relay is the line impedance for $5km$. The Thevenin equivalent impedances are shown in Fig. 8 and 9.

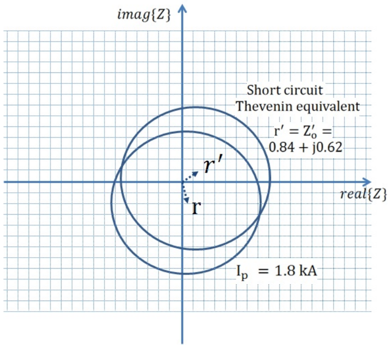

Fig. 8. Thevenin equivalent in short circuit for OCR6 relay

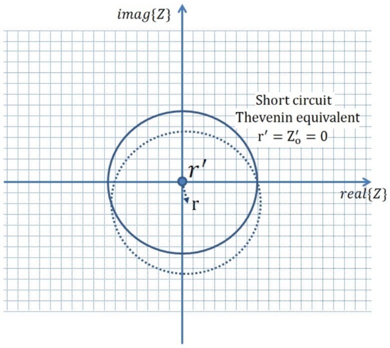

Fig. 9. Thevenin equivalent in short circuit for OCR7 relay

IV. OVERCURRENT RELAYS OPERATION

According to the inverse time characteristic, in high fault currents the operation of overcurrent relays are faster (lower tripping time) than low fault currents. Eq. (9) represents the inverse time characteristic to calculate the tripping time [8].

$$Trip_{time} = \frac{K \times B}{(\frac{(I_f)}{I_p})^{\alpha} - 1} \tag{9}$$

Where, K is time multiplier settings, I_f and I_p are measured fault current value and set current value (pick up current), respectively. For normally inverse case, B and α are considered as 0.14 and 0.02 respectively.

The time multiplier setting (K) for the relays OCR6 and OCR7 are considered as 0.15 and $0.06s$, respectively. The pick up current is also considered as $650A$. To compare the tripping times of the relays OCR6 and OCR7 a three phase current at the end of the line (at $5km$ from the OCR6 relay) is considered. As we mentioned earlier the Thevenin equivalent change when the energy resources are added to the power grid. The short circuit current at the OCR7 relay location is $3.28kA$. According to the inverse time characteristic the tripping time for the OCR6 and OCR7 relays are calculated in two cases, without energy resources and with both energy resources. For the first case the OCR6 and OCR7 relays tripping times are calculated. For OCR6,

$$Trip^{OCR6}_{time} = \frac{0.15 \times 0.14}{(\frac{3.28}{0.65})^{0.02} - 1} = 0.638s \tag{10}$$

Tripping time for the OCR7 relay is,

$$Trip^{OCR7}_{time} = \frac{0.06 \times 0.14}{(\frac{3.28}{0.65})^{0.02} - 1} = 0.255s \tag{11}$$

After connecting the energy resources and according to the fault current and pick up currents which are $I_f = 3.994kA$, $I_p(OCR6) = 0.557$ and $I_p(OCR7) = 0.535kA$ the tripping times are,

$$Trip^{OCR6}_{time} = \frac{0.15 \times 0.14}{(\frac{3.994}{0.557})^{0.02} - 1} = 0.523s \tag{12}$$

$$Trip^{OCR7}_{time} = \frac{0.06 \times 0.14}{(\frac{3.994}{0.535})^{0.02} - 1} = 0.205s \tag{13}$$

As we can see, adding the energy resources to the grid decrease the tripping time. Based on equations (10), (11), (12), and (13) the proposed algorithm improves the tripping times,

$$\frac{0.15 \times 0.14}{(\frac{3.28}{0.65})^{0.02} - 1} - \frac{0.15 \times 0.14}{(\frac{3.994}{0.557})^{0.02} - 1} = 0.115s \tag{14}$$

$$\frac{0.06 \times 0.14}{(\frac{3.28}{0.65})^{0.02} - 1} - \frac{0.06 \times 0.14}{(\frac{3.994}{0.535})^{0.02} - 1} = 0.05s \tag{15}$$

It is clear from the above results that the tripping time has been improved by the proposed relay.

V. CONCLUSION

This paper presented a new algorithm for power grid overcurrent relays. The algorithm takes advantages of the relays tripping time characteristics and pick up current which are adapted to the Thevenin equivalents. The pickup current is transformed to the impedance plane. The transformation and adaptation which are based on a least squares estimation are considered only for the stepwise varying Thevenin equivalent. Examples included the power grids with islanded mode operation or configurations containing wind parks connected to the power grid. The results indicate that the Thevenin equivalent based method improved the tripping time and adapted the pickup current to the Thevenin equivalent impedance.

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