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# Adaptive Protection Algorithm for Overcurrent Relay in Distribution System with DG

**Byung Chul Sung*, Soo Hyoung Lee**, Jung-Wook Park† and A. P. S. Meliopoulos****

**Abstract** – This paper proposes the new adaptive protection algorithm for inverse-time overcurrent relays (OCRs) to ensure their proper operating time and protective coordination. The application of the proposed algorithm requires digital protection relays with microcontroller and memory. The operating parameters of digital OCRs are adjusted based on the available data whenever system conditions (system with distributed generation (DG)) vary. Moreover, it can reduce the calculation time required to determine the operating parameters for achieving its purpose. To verify its effectiveness, several case studies are performed in time-domain simulation. The results show that the proposed adaptive protection algorithm can keep the proper operating time and provide the protective coordination time interval with fast response.

**Keywords**: Adaptive protection algorithm, Coordination time interval, Distributed generation, Inverse-time overcurrent relay, Protective coordination

## 1. Introduction

The overcurrent relays (OCRs) have been most commonly used as an efficient device to protect radial distribution systems. In such systems, the OCRs must operate rapidly to minimize fault duration and damage of equipment. Also, the appropriate time-lag between primary and back-up protections in OCRs must be ensured to avoid unnecessary operation or false trip. In general, the OCR taking its primary protection zone must operate firstly. Then, the OCR for back-up protection should operate only if primary protection fails to operate correctly and after waiting for the appropriate delay duration, which is referred to as the coordination time interval. This means that all protection functions must be coordinated properly with their fast operation for faults occurred in primary zone.

On the other hand, the interest to renewable energies and distributed generation (DG, PV, wind) results in increasing number of installations not only because of its eco-friendly aspects but also its commercial advantages. Since the conventional relays including the OCR operate with fixed parameters (settings), it is difficult to ensure the proper protection operation when operating conditions of radial distribution system are changing as DGs connect and disconnect in the system. This problem becomes more serious if multiple DGs are connected to the system. In particular, the pre-determined coordination between the OCRs is affected by the increased fault current due to the connection of DGs and its reverse flow [1-4]. To solve this problem, a new adaptive protection algorithm is proposed utilizing the capabilities of the digital protection relay such as intelligent electronic device (IED). Because the digital protection relay is equipped with microcontroller and memory, it is possible to program it with the real-time operating scheme and to store the required data. Moreover, it has communication links to exchange data and operating signals between themselves as well as to reset the protective function settings. It is also noted that they can communicate with the upper-level system such as supervisory control and data acquisition (SCADA) system in modern substation. Therefore, it can adjust their operating parameters and characteristics corresponding to the changes in the distribution system [5-9].

In this paper, the proposed adaptive protection algorithm keeps the proper operations and coordination of OCRs with the system data from the digital protection relay even when the operating conditions change due to load variations and/or connection of DGs. Also, it can reduce the computation time required to calculate the operating parameters of OCRs such as pick-up current and time dial setting. The performance of the proposed algorithm is evaluated with several case studies in a radial distribution system by using the power systems computer aided design/electromagnetic transients including DC (PSCAD / EMTDC®) software.

## 2. Inverse-Time Overcurrent Relay

The inverse-time OCR, which is operated by monitoring the magnitude of fault current, is the one of various

† Corresponding Author: School of Electrical and Electronic Engineering, Yonsei University, Seoul, Korea (jungpark@yonsei. ac.kr)
* School of Electrical and Electronic Engineering, Yonsei University, Seoul, Korea (guardchul@yonsei.ac.kr)
** School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0250, USA (resonable21@gmail.com, sakis.m@gatech.edu)
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protection functions. The OCR transfers a trip signal when the fault current exceeds a pre-determined pick-up current, $I_{pick\text{-}up}$. Its inverse-time current characteristic is expressed as (1) and (2), which present the dynamics of induction disk OCR [10].

$$\int_0^{T_0} \frac{1}{t(I)} dt = 1 \tag{1}$$

$$t(I) = \text{TDS}\left[\frac{A}{M^p - 1} + B\right] \tag{2}$$

where $T_0$ is the operating time, $I$ is the fault current seen by the OCR, TDS is the time dial setting, and $M$ is the ratio of $I/I_{pick\text{-}up}$. Also, $A$, $B$, and $p$ are coefficients which so selected as to represent inverse, very inverse, and extremely inverse types of OCR. It is observed from (1) and (2) that the trip time, $t(I)$ is the function of the fault current, $I$, which may vary during the fault. Therefore, the value of $t(I)$ may be also changed according to the time. This reciprocal number of varying $t(I)$ is integrated from zero unless the fault current is reduced below the pick-up current. If the integration value becomes 1, then, the OCR issues a trip command to the OCR. In other words, the fault current is integrated from zero to the operating time, $T_0$.

In most cases, the OCRs are applied to a radial distribution system as shown in Fig. 1. Since the current is flowing from the substation to downward only in one direction, the OCR is connected to the radial line right behind the related bus. Only one OCR is used per a protection zone while two other OCRs are necessary for each direction if the bi-directional flows of fault current are considered. This one-way fault current flowing to downward is passed through a current transformer (CT) between distribution line and OCR. Then, the fault current measured by the CT is used as the input of OCR to determine its operating time. Also, the magnitude of fundamental component of fault current sensed by the CT is sampled as the input for the digital OCR.

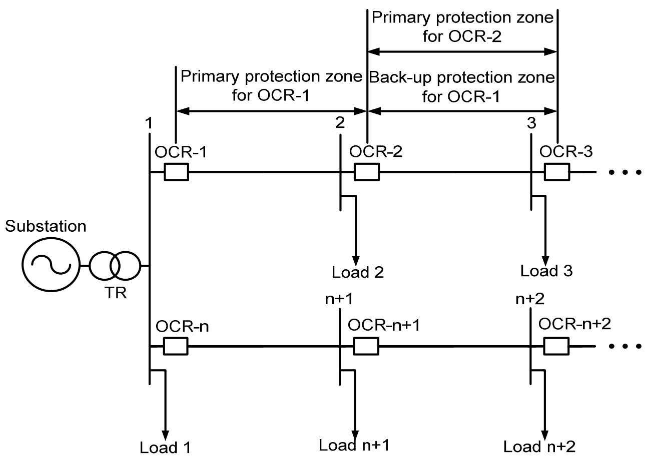



**Fig. 1.** Application of OCRs to a radial distribution system

The primary and back-up protection zones for OCR-1 and OCR-2 are shown in Fig. 1. In general, several protective devices installed in series should have the specified operation sequence as in Fig. 1. This relationship among protective devices are said to be coordinated or selective.

In order to isolate the minimum possible faulted area with, the relays of primary protection zone should be firstly operated depending on the location of the fault, and their associated back-up relays should trip only when the primary relays are not operated correctly. For example, if a fault occurs at the point between the bus 2 and the bus 3 in Fig. 1, the OCR-2 operates as the primary protection to minimize the outage area, which must be isolated by the operation of the breaker. Also, the OCR-1 should serve as the back-up protection to cut off the fault current if the OCR-2 cannot operate normally. Moreover, it is essential to maintain the proper time interval between the primary and back-up protection. This is called the coordination time interval (CTI) [11-12], which is usually 0.2 s to 0.5 s. This CTI is required to apply all protection devices such as even reclosers and fuses as well as relays in a distribution system. Its associated equation is given as in (3).

$$t_{back-up} - t_{primary} \geq \text{CTI} \tag{3}$$

where $t_{primary}$ and $t_{back\text{-}up}$ are the operation times of primary and back-up protections, respectively. The operating time of the back-up protection is generally larger than that of the primary protection. Therefore, the difference between them should exceed the CTI as (3), which has 0.2 sec as the minimum value as mentioned before.

When the DG is connected to a radial distribution system, it can increase the fault current and possibly reverse the direction of power flow. The latter case is illustrated in Fig. 2 that the flow of fault current is changed by connecting the DG at bus 2. In other words, the fault current from the DG flows reversely to the fault location, F1 in Fig. 1. Then, it is added to the fault current flowing from the substation. This results in increasing the fault

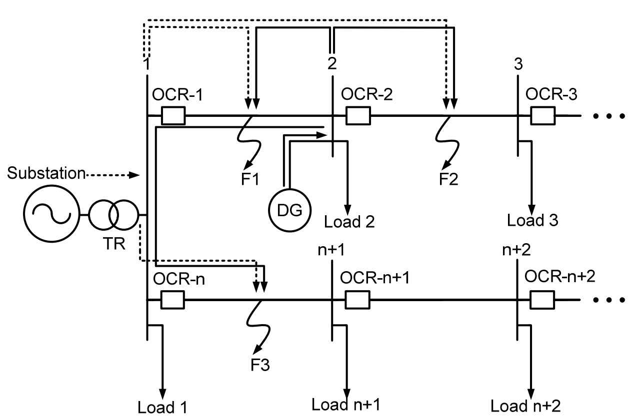



**Fig. 2.** Fault current increased by connecting the DG and its reverse power flow

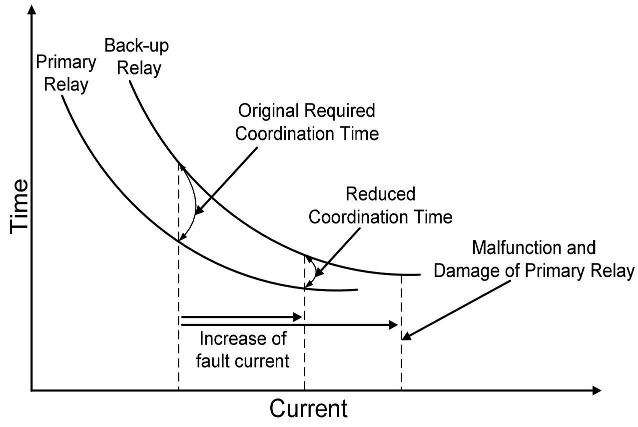



**Fig. 3.** Protective coordination between the primary and back-up relays considering CTI when the DG is connected

current when compared to the case without the DG. Moreover, when the fault occurs at the fault location, F2, it is also increased due to the DG even though there is no reverse flow of the fault current. If the fault occurs at the fault location, F3 on the adjacent feeder, its magnitude sensed by OCR-n also becomes larger since the fault current from DG flows reversely to the F3. Therefore, the OCR-n might function incorrectly unless its operating parameters are changed properly [2, 4, 12].

In summary, the increased fault current can have the undesirable effect on the operation of OCRs in the distribution system. Because the OCRs have the inverse-time current characteristics as given in (1) and (2), their operating times are decreased correspondingly to the amount of increase in fault current. In other words, the larger the magnitude of fault current becomes, the faster the OCR will operate. However, note that a too-fast operation of relay may lead to unnecessary removal of a larger portion of the system.

As shown in Fig. 3, the primary OCR might have difficulty in coordinating with the back-up OCR when the fault current is increased. That is, the required coordination time is reduced as the available fault current increases. This results in mis-coordination. If this fault current is further increased over the rated value of primary relay, it is unable to coordinate with the back-up relay, resulting in possible misoperation. Therefore, the operating parameters of OCRs must be correctly adjusted for the prevailing fault conditions with the direction-sensitive capability of whether the current flows in either direction [4].

## 3. Proposed Adaptive Protection Algorithm

Optimization of the operating sequence of all protective devices while maintaining their protective coordination in the presence of multiple DGs is very complex. In particular, as the number of OCRs and DGs increases, the calculation time required to determine their operating parameters will also increase [6, 7, 9]. For this reason, the adaptive protection algorithm to drastically reduce the computational effort is proposed in this section.

### 3.1 Determination of pick-up current

Assume that the pick-up current, $I_{pick\text{-}up}$ of OCR is calculated periodically from the monitored current. It will have different value whenever the system configuration is changed. For each time interval, the load current calculated after a fixed time from its starting point is used to determine the value of $I_{pick\text{-}up}$. The provision of a time delay to stabilize the distribution system is necessary to select a stable load current corresponding to the connection of DG. Then, the value of $I_{pick\text{-}up}$ is determined as shown in (4).

$$I_{pick-up} = I_L\big|_N \times 1.5 \tag{4}$$

where $I_L|_N$ is the load current calculated after the fixed time from its starting point of $N$-th time interval. As (4), the new $I_{pick\text{-}up}$ is set to be 1.5 times the selected load current because a safety margin must be given to it. This safety margin is necessary so that the OCR operate by the normal load current of the steady-state, which is used to determine $I_{pick\text{-}up}$. In other words, the OCR will trip the intact part of the power system if the value of $I_L|_N$ is set as the pick-up current. Moreover, the multiplier, 1.5, can be adjusted to provide the required safety margin.

Therefore, the pick-up current can be obtained with the load current, which reflects the condition of the system. Note that the length of time interval must be properly set not to calculate the pick-up current too frequently. After another time delay, the value of $I_{pick\text{-}up}$ is applied to determine the operating parameters of OCR. This time delay is required so that the OCR operates with its pre-determined parameters in case of the fault occurred at the point, where the $I_L|_N$ is obtained. In other words, if this fault current is used as the pick-up current of OCR directly, it might be too large to separate the fault area from the distribution system correctly. Moreover, this waiting period provides the sufficient time to calculate the new value of time dial setting (TDS), which is described in the following section.

### 3.2 Determination of time dial setting

As mentioned previously, the OCR has two important operating parameters, the pick-up current and TDS. The pick-up current is firstly calculated with the load current by (4). Then, the new TDS, $TDS_{new}$ is computed by (5) to maintain its original operating time and CTI without regard to the change of system condition. In other words, the $TDS_{new}$ is determined to make the OCR operate similarly to the pre-determined operation time according to the OCR characteristic in (2).

$$\text{TDS}_{new}=\text{TDS}\frac{(A+B(M^{p}-1))(M'^{p}-1)}{(A+B(M'^{p}-1))(M^{p}-1)} \quad (5)$$

where the $A$, $B$, and $p$ are the associated coefficients of OCR, and $M'$ is the ratio of $I/I_{pick\text{-}up}$ for the current time interval. The $M'$ becomes different from the $M$ determined form the previous time interval if the $I_{pick\text{-}up}$ and fault current is varied depending on the system condition. Their relationship is defined as (6)

$$M' = kM \quad (6)$$

In (5), the values of $A$, $B$, $p$, and TDS are kept to be constant even after the system condition is changed. Note that the $M$ can be known by the fault current data stored in the OCR memory. Moreover, analysis of off-line fault current in a distribution system is conducted if it is required to update with the changed data. Therefore, the $M'$ can be easily calculated by transmitting it to the OCR through the communication links. Consequently, it is possible to obtain the $\text{TDS}_{new}$ rapidly because all values in (5) are already known. As well, the TDS can also be obtained more easily for the case that loads and OCR characteristics are changed. In summary, when the load is changed, the update of fault current data is not necessary because it may remain constant in practice. In contrast, the pick-up current is replaced by the new one according to variations of load current. Therefore, only $M$ is changed into $M'$, and the $\text{TDS}_{new}$ is obtained by using (5). Also, if only characteristics of the OCR are changed, the new TDS is computed with new coefficients, as given by (7). In this case, the $M$ for previous time interval is the same as the $M'$ for current time interval because there is no change in both pick-up current and fault current.

$$\text{TDS}_{new}=\text{TDS}\frac{(A_1+B_1(M^{p_1}-1))(M'^{p_2}-1)}{(A_2+B_2(M'^{p_2}-1))(M^{p_1}-1)} \quad (7)$$

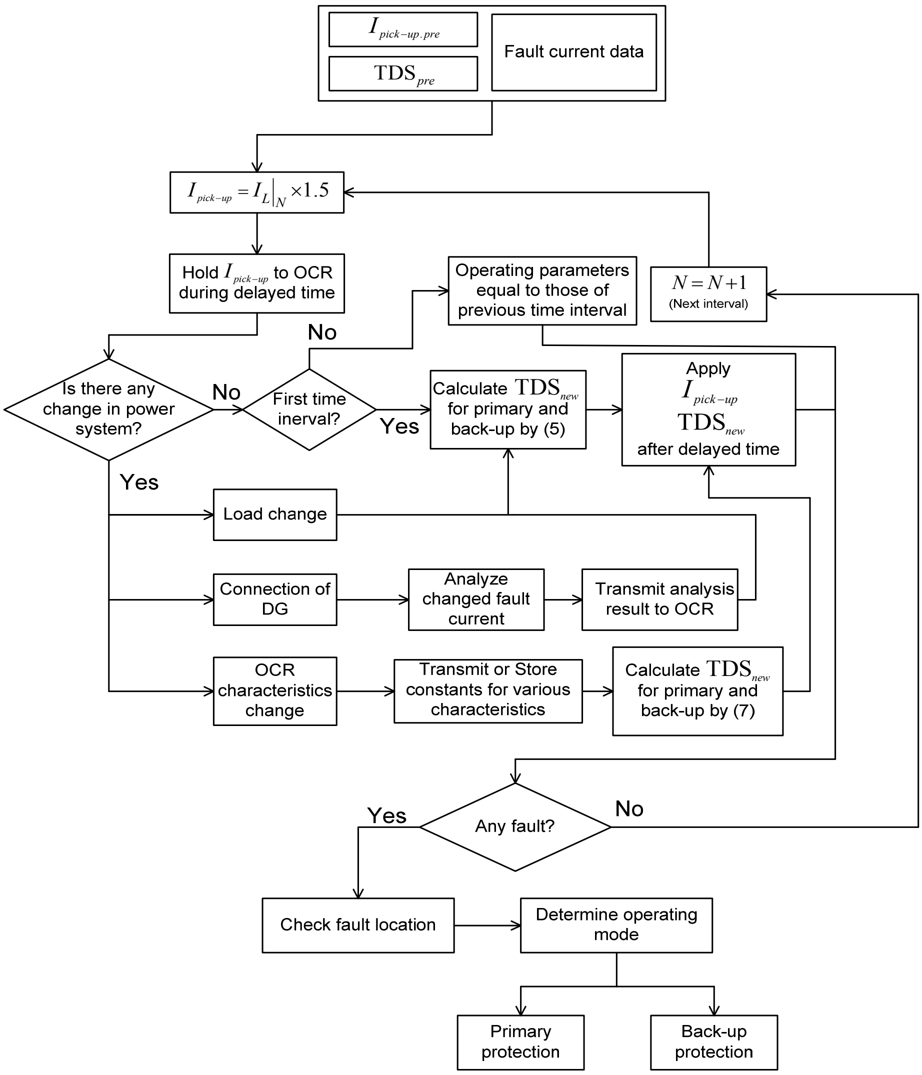



**Fig. 4.** Procedure to implement the proposed adaptive protection algorithm

where ($A_1$, $B_1$, $p_1$) and ($A_2$, $B_2$, $p_2$) are the coefficients for previously and newly chosen characteristics, respectively.

By the proposed method, the $TDS_{new}$ in (7) can be simply determined in the case that multiple transitions occur. In other words, after the pick-up current and TDS are calculated newly, these operating parameters are then applied to the OCR at the same time.

### 3.3 Procedure to implement the proposed algorithm

The overall procedure to implement the proposed adaptive protection algorithm is shown in Fig. 4.

Firstly, the values of pre-determined operating parameters, which are Ipick-up.pre and $TDS_{pre}$, are obtained. Also, the fault current data is stored. Thereafter, the value of $I_{pick\text{-}up}$ seen by the OCR is calculated with the information of load current, and held during the time delay before the proposed algorithm is applied to the OCR.

Without any changes in a distribution system, it is possible that the value of $I_{pick\text{-}up}$ becomes different from that in the previous time interval. In most cases, it occurs in the first time interval. In this case, the fault current data stored in the OCR is used to find the values of $M$ and $M'$ in (6) until the fault current data is changed according to the system condition. Then, the two $TDS_{new}$ corresponding to close-in faults for both primary and back-up protection zones are computed by (5) for each OCR during the short time delay. Note that the last OCR in line uses the TDS for only primary protection zone because it avoids providing the back-up protection. After determining the values of $I_{pick\text{-}up}$ and two $TDS_{new}$, they are used to replace the pre-determined operating parameters.

In a steady-state condition, the next interval is updated with the above new operating parameters. Then, the value of $I_{pick\text{-}up}$ is calculated again. If there are still no changes in the system, there is no need to calculate the two $TDS_{new}$ because the value of $I_{pick\text{-}up}$ is identical to that for the previous time interval. In other words, the TDSs are kept to be constant with the same $I_{pick\text{-}up}$ without changes in system condition.

In the case that there is a change in system by load variation, or connection of DGs, the value of $I_{pick\text{-}up}$ becomes different from that of $I_{pick\text{-}up.pre}$ or $I_{pick\text{-}up}$ determined in the previous time interval. This does not apply to the case that the characteristic of OCR is changed. Then, the two $TDS_{new}$ for the primary and back-up protection are determined as previously. In particular, the updated fault current data is unnecessary for the cases of change in load and OCR's characteristic, as mentioned in sub-section 3.2. Therefore, the two TDSs for these two cases are computed by using (5) and (7), respectively. In contrast, the connection of DG requires updating the fault current data. After transmitting this updated information to the OCR, the $M$ and $M'$ are calculated by (6). Thereafter, the $TDS_{new}$ is obtained by (5). If the condition of system is not changed any more, the applied operating parameters are fixed.

When a fault occurs in the distribution line, the OCR will respond according to the operating parameters, $I_{pick\text{-}up}$ and $TDS_{new}$, which are calculated in above. Then, each OCR determines the operating mode between primary and back-up protections by checking the fault location, which can be found by comparing the monitored fault current to the stored data. Finally, the operating modes of OCR are selected with the proper TDS according to whether it corresponds to the primary or back-up protection.

## 4. Test Distribution System and OCR Setting

A test system has been used to evaluate the performance of proposed protection algorithm. The test distribution system is shown in Fig. 5. This distribution system consists of a 154-kV substation, a 154/22.9-kV transformer of 10 MVA, four loads on the 22.9-kV line, and three OCRs. The load and line impedance data are given in Tables 1 and 2, respectively. It is assumed that a three-phase short-circuit fault with its fault impedance, $R_f$ of 0.01 Ω is applied at bus 4. Then, the system is protected by three coordinated OCRs, which are named OCR-1, OCR-2, and OCR-3. The CT ratios of each OCR are set to be 200:5, 150:5, and 100:5, respectively.

The operating characteristics of three OCRs in Table 3 are selected based on the IEEE standard C37.112 [10]. Note that a three-phase short-circuit fault might occur at each line. Then, according to the fault location, the close-in

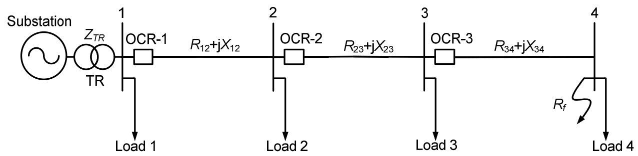



**Fig. 5.** Radial distribution test system

**Table 1.** Load data

| | Load | | |
|---|---|---|---|
| | $S$ [MVA] | $P$ [MW] | $Q$ [Mvar] |
| Load 1 | 3.35 | 3 | 1.5 |
| Load 2 | 2.02 | 2 | 0.3 |
| Load 3 | 1.51 | 1.5 | 0.15 |
| Load 4 | 3.06 | 3 | 0.6 |

**Table 2.** Line impedances

| Line | | Impedance [Ω] | |
|---|---|---|---|
| From bus | To bus | Series resistance ($R$) | Series reactance ($X$) |
| 1 | 2 | 0.02 | 4.0 |
| 2 | 3 | 0.02 | 6.4 |
| 3 | 4 | 0.01 | 8.0 |
| $Z_{TR}$ | | 0 | 5.6 |
| $R_f$ | | 0.01 | 0 |
| Total | | 0.06 | 24 |

**Table 3.** Constants and exponent for various OCR characteristics from IEEE Standard C37.112

| Characteristic | $A$ | $B$ | $p$ |
|---|---|---|---|
| Moderately inverse (MI) | 0.0515 | 0.1140 | 0.02 |
| Very inverse (VI) | 19.61 | 0.491 | 2.0 |
| Extremely inverse (EI) | 28.2 | 0.1217 | 2.0 |

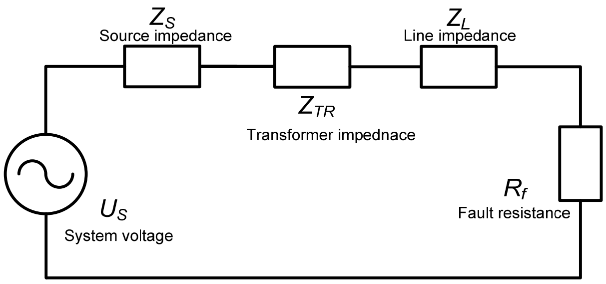



**Fig. 6.** Equivalent circuit of distribution system by the impedance method

and far-bus faults have their maximum and minimum values, respectively. In general, the equivalent circuit of distribution system shown in Fig. 6 is used to calculate the short-circuit current by using the impedance method. Each part of power system such as external grid, transformer, and line is converted to its impedance [13-14].

Then, the operating parameters of OCRs are determined after calculating the short-circuit current with the load and impedance data in Tables 1 and 2. For example, when a three-phase short-circuit occurs at bus 4 (therefore, it is the far-bus fault of OCR-3), it is calculated by both the value of total series impedance from source to fault location, which is the sum of the impedance for the equivalent circuit in Fig. 6, and the voltage level of the power system as (8).

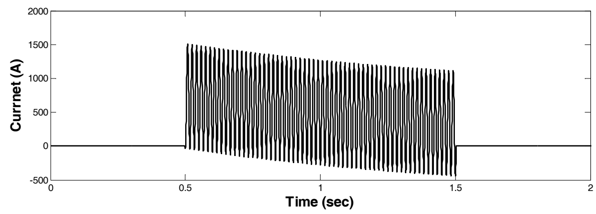
$$I_{sc3} = \frac{U_S}{\sqrt{3} \times \left| Z_S + Z_{TR} + Z_L + R_f \right|} = 550.89 \text{ [A]} \tag{8}$$

where $I_{sc3}$ is the magnitude of the three-phase short-circuit current, and $U_S$ is the phase-to-phase voltage. Because the source impedance is so small that it can be neglected, the total series impedance from source to fault location is $0.06+j24[\Omega]$, and its magnitude is approximately 24 Ω.

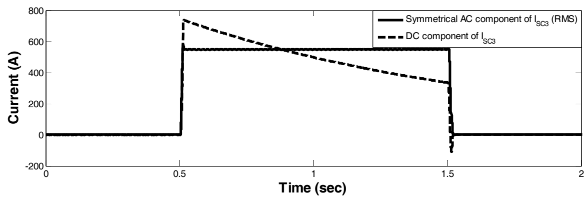
The waveform of short-circuit current flowing from bus 3 to bus 4 is shown in Fig. 7(a). The short-circuit current consists of the DC component, which is decreased exponentially based on the ratio of resistance to reactance, and the symmetrical AC component. The responses of these two components are shown in Fig. 7(b). As mentioned previously, the magnitude of the symmetrical AC component is used as the input of OCRs. It is known from Fig. 7(b) that the root-mean-square (RMS) value of symmetrical AC component is obtained as approximately 550 A. Note that this value is almost same as that of short-circuit current calculated by (8).

**Table 4.** Pre-determined operating parameters of OCRs

| | | | | OCR-1 | OCR-2 | OCR-3 |
|---|---|---|---|---|---|---|
| $I_{sc3}$ [A] | Line12 | | CI | 2360.9 | - | - |
| | | | FB | 1377.2 | - | - |
| | Line23 | | CI | 1377.2 | 1377.2 | - |
| | | | FB | 826.33 | 826.33 | - |
| | Line34 | | CI | 826.33 | 826.33 | 826.33 |
| | | | FB | 550.89 | 550.89 | 550.89 |
| CT ratio | | | | 200:5 | 150:5 | 100:5 |
| Characteristic | | | | VI | VI | MI |
| $I_{pick\text{-}up}$ [A] | | | | 6.0 | 5.0 | 5.5 |
| TDS | | | | 0.40 | 0.33 | 0.13 |
| $T_o$ [sec] | Cal | Line12 | CI | 0.2783 | - | - |
| | | | FB | 0.4421 | - | - |
| | | Line23 | CI | - | 0.2397 | - |
| | | | FB | - | 0.3825 | - |
| | | Line34 | CI | - | - | 0.1775 |
| | | | FB | - | - | 0.2193 |
| | Sim | Line12 | CI | 0.2860 | - | - |
| | | | FB | 0.4500 | - | - |
| | | Line23 | CI | - | 0.2467 | - |
| | | | FB | - | 0.3915 | - |
| | | Line34 | CI | - | - | 0.1837 |
| | | | FB | - | - | 0.2262 |




(a)




(b)

**Fig. 7.** Waveforms of $I_{sc3}$ when a three-phase short-circuit occurs at bus 4 (a) response of a-phase $I_{sc3}$ (b) symmetrical AC and the DC component of $I_{sc3}$

In Table 4, the short-circuit currents as close-in (CI) and far-bus (FB) faults are obtained in each line of test distribution system by simulation. Also, their values are compared with those of short-circuit currents calculated by the impedance method as given in (8). It is clearly observed from Table 4 that as the fault location is closer to the substation, the magnitude of short-circuit current becomes increasing. After calculating the short-circuit current in each line, the operating parameters of all OCRs are determined so that the distribution system can be protected within a proper time. It is assumed that the CI fault current flowing toward downward in line is equal to the FB fault current flowing toward upward in line [11]. Thereafter, all parameters and selected characteristics of three OCRs are given in Table 4. The operating times obtained from simulation are the times when the integration becomes one as given in (1) and its operating signal is released. When they are compared with the calculated operating times by (2), the results show that they are almost same. For both cases, the CTI of 0.2 s is properly determined for all lines. Also, the time interval required to calculate the new pick-up current and TDSs is assumed to be 1 s. Then, the time delays for measuring the load current and calculating new TDSs of OCRs are 0.3 s and 0.1 s, respectively.

## 5. Performance Evaluation

To evaluate the performance of the proposed algorithm, the condition of distribution system is changed by connecting the DG of 4 MVA at bus 2 as shown in Fig. 8. The output voltage of DG is 10 kV, and it is connected to the system through a 10/22.9 kV transformer.

First, the pick-up current is calculated based on the load current after 0.3 s from the starting point of time interval, which is 0.5 s. It is known from the result in Fig. 9 that the load current seen by OCR-1 is decreased to 1.61 A after

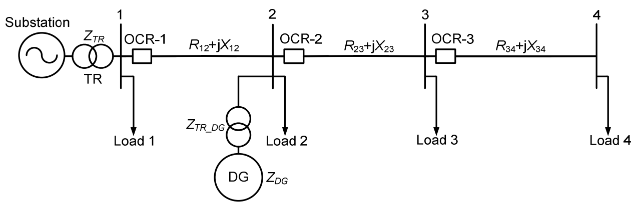



**Fig. 8.** Distribution system with the DG connected to bus 2 through the transformer

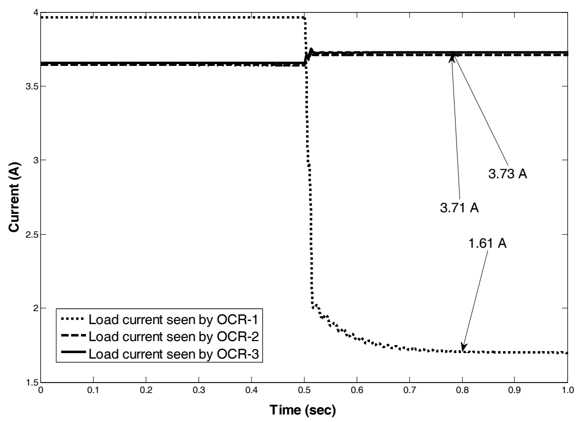



**Fig. 9.** Load current seen by each OCR at the secondary side of CT before and after the connection of DG

connecting the DG. In contrast, the load currents seen by OCR-2 and OCR-3 are slightly changed.

When a three-phase short-circuit with the fault impedance of $R_f$ is applied to bus 4, the equivalent circuit considering the connection of DG is formed as shown in Fig. 10 by applying the impedance method. In this case, there are two sources of fault current, and it is described that the two sources are connected in parallel. Moreover, the magnitude of short-circuit current depends on the location, where the DG is connected. Therefore, it is necessary to consider the ratio $l$, which is defined as the distance from substation to DG over the distance from source to fault location. Since the line distance can be equivalent with its corresponding impedance, the distance between any two buses is represented by the impedance data in Tables 2 and 5. Then, the total summation of all impedances in the equivalent circuit in Fig. 10 is calculated by (9).

$$Z_{tot} = \frac{(Z_S + Z_{TR} + l \cdot Z_L) \cdot (Z_{TR\_DG} + Z_{DG})}{Z_S + Z_{TR} + l \cdot Z_L + Z_{TR\_DG} + Z_{DG}} + (1-l) \cdot Z_L \quad (9)$$

where $Z_{TR\_DG}$ and $Z_{DG}$ are the impedance of transformer connected to the DG and the DG itself, respectively. In the equivalent circuit, the impedances are referred to the secondary side of the transformer, as given in Table 5. Also, the value of $l$ is 0.4 in this case.

$$I_{sc3} = \frac{U_S}{\sqrt{3} \times |Z_{tot}|} = \frac{22900}{\sqrt{3} \times 18.42} = 717.66 \ [A] \quad (10)$$

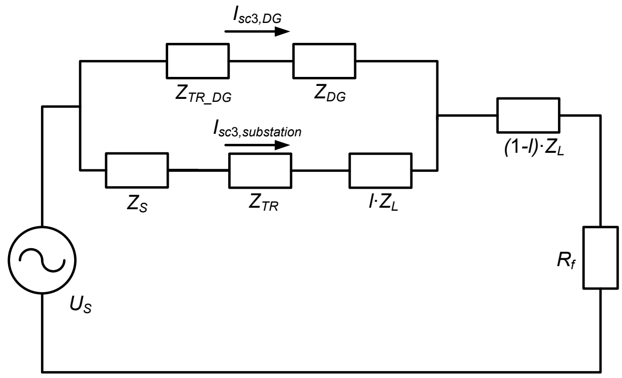



**Fig. 10.** Equivalent circuit when the DG is connected

**Table 5.** Impedance data of DG transformer and DG itself

| Impedance | Impedance [Ω] | |
|---|---|---|
| | Series resistance ($R$) | Series reactance ($X$) |
| $Z_{DG}$ | 0.05 | 0.3195 |
| $Z_{TR\_DG}$ | 0 | 1.0 |
| Total | 0.05 | 1.3195 |
| Impedance by reflecting referred to secondary side | 0.2622 | 6.9196 |

$$I_{sc3,substation} = I_{sc3} \left| \frac{Z_{TR\_DG} + Z_{DG}}{Z_S + Z_{TR} + l \cdot Z_L + Z_{TR\_DG} + Z_{DG}} \right| \quad (11)$$

Finally, the total short-circuit current, $I_{sc3}$, which is the sum of $I_{sc3,\ DG}$ and $I_{sc3,\ substation}$ in the parallel circuit of Fig. 10, is computed by (10) similar to (8). Moreover, since OCR-1 can monitor only $I_{sc3,\ substation}$ from Fig. 8 and the value of $I_{sc3}$ is divided into $I_{sc3,\ DG}$ and $I_{sc3,\ substation}$, the value of the input for it can be calculated by (11) according to the equivalent circuit. On the other hand, the short-circuit current for the CI fault at line34 can be also calculated by the same manner as (10). In this case, the value of $l$ is 0.6 because the DG is still connected at bus 2, however the fault occurs close to bus 3 [15].

After connecting the DG, the short-circuit currents, $I_{sc3}$ seen by the OCRs for the CI and FB faults at line34 are given in Table 6. However, the operating times, $T_o$ of OCR-2 and OCR-3 changed by the connection of DG under the previous setting in Table 4 are 0.2615 s and 0.1542 s, respectively. Because they operate quickly, the difference of $T_o$ between them is about 0.11 s, which is smaller than the required minimum CTI of 0.2 s. This might cause a protective coordination problem.

When the proposed method in Fig. 4 is applied, the new pick-up currents for OCR-1, OCR-2 and OCR-3 are calculated by (4), they are 2.42 A, 5.57 A, and 5.60 A, respectively. Then, two $TDS_{new}$ fitting to these new pick-up currents are obtained so that the $T_o$ of OCRs is kept to be the previously established values required as given in Table 4. The values of $TDS_{new}$ and $T_o$ are given in Table 6. It is observed that $T_o$ for OCR-2 and OCR-3 are now changed to 0.3910 s and 0.1835 s, respectively. The difference is 0.2075 s, which is greater than the required minimum CTI of 0.2 s. Therefore, they satisfy the protective coordination requirements.

Since the short-circuit occurs at line34, OCR-2 and OCR-3 operate as back-up and primary protection, respectively. Then, the CI fault current at bus 3 is considered to evaluate the protection coordination between the OCR-2 and the OCR-3. Therefore, the OCR-3 setting $TDS_{new}$ is for the primary protection. In contrast, the $TDS_{new}$ for OCR-2 is determined for the back-up protection by the CI fault at line34. Because the OCR-3 is the last protective device in the radial line, the setting $TDS_{new}$ is for the primary protection only. Therefore, the proper protection can be still provided by the OCR-3 even though the $T_o$ for the primary protection is slightly increased to 0.2343 s from 0.2262 s in Table 4.

Differently from the above case, the OCR-2 operates as the primary protection if the short-circuit occurs at line23 in Fig. 8. Moreover, the OCR-1 operates as the back-up protection. In this case, the new pick-up currents for OCR-1, OCR-2 and OCR-3 are equal to the above case. However, the $T_o$ of OCR-1 and OCR-2 are changed by connecting the DG. As given in Table 7, those values are 0.4505 s and 0.1812 s, respectively. It is observed that the $T_o$ of OCR-2 is reduced greatly from 0.2467 s (see Table 4) to 0.1812 s. This is because only OCR-2 is affected by the short-circuit current from the connected DG. Therefore, the difference of 0.2693 s in $T_o$, which is still valid for the protective coordination because it is larger than the pre-determined CTI of 0.2 s. Also, the values of $TDS_{new}$ and $T_o$ with new setting for the OCR-1 and OCR-2 are given in Table 7. The $TDS_{new}$ of OCR-2 is 0.4424 whereas that for the back-up protection is 0.4569 as given in Table 6. This means that the OCR-2 can select the operating mode with different $TDS_{new}$ depending on the fault location. When the OCR-2 operates as the primary protection based on the related $TDS_{new}$, 0.4424, the $T_o$ for CI fault at line23 is 0.2455 s, which is very similar to the previously established $T_o$ of 0.2467 s (in Table 4). Moreover, the CTI between the OCR-1 and OCR-2 decreases from 0.2693 s to 0.2030 s, which is the same to the pre-determined CTI and still satisfies the required minimum CTI of 0.2 s. For the FB fault at line23, it is verified that line23 can be protected by the primary protection of OCR-2 because the To of 0.3788 s is similar to its pre-established value of 0.3915 s in Table 4.

**Table 6.** New operating parameters of OCRs by connecting DG to Bus2 when fault occurs at Line34

| | | | OCR-1 | OCR-2 | OCR-3 |
|---|---|---|---|---|---|
| $I_{sc3}$ [A] | | CI | 531.62 | 1268.48 | 1268.48 |
| | | FB | 300.77 | 717.66 | 717.66 |
| $T_o$ with old setting [sec] | Cal | CI | - | 0.2538 | 0.1484 |
| | | FB | - | - | 0.1900 |
| | Sim | CI | - | **0.2615** | **0.1542** |
| | | FB | - | - | 0.1965 |
| Load current at 0.8 sec [A] | | | 1.61 | 3.71 | 3.73 |
| New pick-up current [A] | | | **2.42** | **5.57** | **5.60** |
| *k* for CI | | | - | 1.3780 | 1.5077 |
| New TDS | | | - | **0.4569** | **0.1544** |
| $T_o$ with new setting [sec] | Cal | CI | - | 0.3825 | 0.1775 |
| | | FB | - | - | 0.2277 |
| | Sim | CI | - | **0.3910** | **0.1835** |
| | | FB | - | - | 0.2343 |

**Table 7.** New operating parameters for connection of DG at Bus2 with fault at Line23

| | | | OCR-1 | OCR-2 | OCR-3 |
|---|---|---|---|---|---|
| $I_{sc3}$ [A] | | CI | 1377.19 | 3286.13 | - |
| | | FB | 531.62 | 1268.48 | - |
| $T_o$ with old setting [sec] | Cal | CI | 0.4421 | 0.1755 | - |
| | | FB | - | 0.2538 | - |
| | Sim | CI | **0.4505** | **0.1812** | - |
| | | FB | - | 0.2618 | - |
| Load current at 0.8 sec [A] | | | 1.61 | 3.71 | 3.73 |
| New pick-up current [A] | | | **2.42** | **5.57** | **5.60** |
| *k* for CI | | | 2.4793 | 2.1419 | - |
| New TDS | | | **0.7514** | **0.4424** | - |
| $T_o$ with new setting [sec] | Cal | CI | 0.4421 | 0.2397 | - |
| | | FB | | 0.3704 | - |
| | Sim | CI | **0.4485** | **0.2455** | - |
| | | FB | | 0.3788 | - |

## 6. Conclusions

This paper proposed a new adaptive protection algorithm for digital overcurrent relays (OCRs) in radial distribution systems that adapts to changes in a distribution system due to connecting/ disconnecting DGs. The proposed method can be applied to the intelligent electronic devices (IED) such as digital (numerical) protection relays because these devices can provide the functions required for data processing, data storage, and communication links. The protection performance of the proposed method was evaluated with simulations on an example system and several case studies. The results showed that the operating time and coordination time interval (CTI) are almost same as their pre-determined values while the operating parameters of OCRs are automatically updated by the proposed simple procedure. Therefore, it could reduce the required calculation time.

In future studies, the adaptive protection algorithm for bi-directional flows of fault currents in both radial and loop distribution systems is will be investigated.

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**Byung Chul Sung** received the B.S. and M.S. degree from the School of Electrical and Electronic Engineering, Yonsei University, Seoul, Korea, in 2006 and 2009, respectively. He is currently pursuing his Ph.D. degree in Yonsei University. His research interests are in power system operation and control, fault-current-limiter (FCL) control connected power grid, development of bi-directional protection coordination technique for distributed generation.

**Soo Hyoung Lee** received the B.S. and Ph.D. degrees from the School of Electrical and Electronic Engineering, Yonsei University, Seoul, Korea, in 2008 and 2012, respectively. He is currently a Post-doctoral Research Associate in the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA. His research interests are in load flow of power system, optimization of grid connected distributed generation systems, antiislanding algorithms and inverter control for distributed generation systems, and measurement based load modeling. He was the recipient of the Gold Prize Paper Award from the TMS Institute of Technology and Second Prize Paper Award from the Yonsei Electric Power Research Center.

**Jung-Wook Park** was born in Seoul, Korea. He received the B.S. degree (summa cum laude) from the Department of Electrical Engineering, Yonsei University, Seoul, Korea, in 1999, and the M.S.E.C.E. and Ph.D. degrees from the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, USA in 2000 and 2003, respectively. He was a Post-doctoral Research Associate in the Department of Electrical and Computer Engineering, University of Wisconsin, Madison, USA during 2003~2004, and a Senior Research Engineer with LG Electronics Inc., Korea during 2004–2005. He is currently an Associate Professor in the School of Electrical and Electronic Engineering, Yonsei University, Seoul, Korea. He is now leading the National Leading Research Laboratory (NLRL) designated by Korea government to the subject of integrated optimal operation for smart grid. He is also a chair of Yonsei Power and Renewable Energy FuturE technology Research Center (Yonsei-PREFER) in School of Electrical and Electronic Engineering, Yonsei University, Seoul, Korea. His current research interests are in power system dynamics, renewable energies based distributed generations, power control of electric vehicle, and optimization control algorithms. Prof. Park was the recipient of Second Prize Paper Award in 2003 from Industry Automation Control Committee and Prize Paper Award in 2008 from Energy Systems Committee of the IEEE Industry Applications Society (IAS). He is currently a vice chair of Intelligent Systems Technical Applications Committee of IEEE Computational Intelligence Society (CIS)

**A. P. S. Meliopoulos** was born in Katerini, Greece, in 1949. He received the M. E. and E. E. diploma from the National Technical University of Athens, Greece, in 1972; the M.S.E.E. and Ph.D. degrees from the Georgia Institute of Technology in 1974 and 1976, respectively. In 1971, he worked for Western Electric in Atlanta, Georgia. In 1976, he joined the Faculty of Electrical Engineering, Georgia Institute of Technology, where he is presently a Georgia Power Distinguished Professor. He is active in teaching and research in the general areas of modeling, analysis, and control of power systems. He has made significant contributions to power system grounding, harmonics, and reliability assessment of power systems. He is the author of the books, Power Systems Grounding and Transients, Marcel Dekker, June 1988, Lightning and Overvoltage Protection, Section 27, Standard Handbook for Electrical Engineers, McGraw Hill, 1993. He holds three patents and he has published over 220 technical papers. In 2005 he received the IEEE Richard Kaufman Award and in 2010 the George Montefiori Award. Dr. Meliopoulos is the Chairman of the Georgia Tech Protective Relaying Conference, a Fellow of the IEEE and a member of Sigma Xi.