A Faulty Feeder Selection Method for Distribution Network with Unintentional Resonance in Zero Sequence Circuit

Mert Bekir Atsever and Mehmet Hakan Hocaoglu

***Abstract*—Faulty feeder selection is a challenging task for distribution system operator due to the low earth fault current magnitudes in compensated networks. However, extensive cable usages, especially in metropolitan cities causes unintentional resonance in the network earthed through inductance or grounding transformer. The unintentionally resonated networks are not designed like intentionally compensated networks where faulty feeder should be isolated in a predetermined time. There are transient zero sequence current based methods, particularly synthesized for compensated networks to identify faulty feeders. However, zero sequence-based faulty feeder selection methods have drawbacks in the presence of underground cables. Further, transient zero sequence current is prone to many parameters such as capacitive imbalance and fault resistance.**

In this study, a transient negative sequence current based faulty feeder selection method is proposed. The effectiveness of the proposed method is demonstrated in a simulated 151-node distribution network. EMTP simulations are carried out by considering different fault inception times, fault resistance and capacitive imbalance of the system. Results show that negative sequence current offers selective faulty feeder selection and no false trip is observed in unintentionally resonating distribution network.

***Keywords*—cable, false trip, negative sequence, transient analysis.**

NOMENCLATURE AND ABBREVIATION

E	phase voltage.
$\vec{I}_{0,F,R}$	zero sequence current seen by the $R_{1,1}$
$\vec{I}_{0,H,R}$	zero sequence current seen by the $R_{2,1}$
$\vec{I}_{0,S,R}$	zero sequence current seen by the $R_{S,S}$
$\vec{I}_{F,0}$	earth fault current magnitude in fault point
$\vec{I}_{0,C,F}$	capacitive current circulating faulted feeder
$C_{0,F}$	zero sequence capacitance of the faulted part
$C_{0,H}$	zero sequence capacitance of the healthy part
$C_{0,T}$	the total zero sequence capacitance
$L_{0,N}$	zero sequence inductance of the grounding transformer
$L_{0,F}$	zero sequence inductance of the faulted part
$R_{0,F}$	zero sequence resistance of the faulted part
$i_{0,H,R}$	transient zero sequence seen by the $R_{2,1}$
$i_{0,F,R}$	transient zero sequence seen by the $R_{1,1}$
$i_{0,S,R}$	transient zero sequence seen by the $R_{S,S}$
$SSZSCC$	Steady-State Zero Sequence Current Characteristic
$TZSCC$	Transient Zero Sequence Current Characteristic

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I. INTRODUCTION

SINGLE line to earth faults are the most common fault type in distribution networks [1]. Neutral earthing treatment determines the earth fault current characteristic. Different neutral earthing treatments have been used in order to deal with the undesirable effects of the earth fault. Differences are mainly due to the conditions of the environment, preferences of operators and regulations of the countries [2]. The diversity of neutral earthing types increases earth fault protection complexity. Even so, whichever neutral earthing treatment is used, faulty feeder must be selected and isolated correctly. Stead-state methods, transient methods and signal injection methods have been used in order to detect the faulty feeder during the single line to earth faults [3]. Selection of these methods mainly depends on network topology and neutral earthing treatment.

Steady-state methods can be applied on the solidly and resistively earthed distribution networks without depending on the line types. However, faulty feeder detection methods depend on the line type in isolated networks. Low-level earth fault current flows in overhead line dense distribution networks. Zero sequence current magnitude of the steady-state region is not a reliable indicator for faulty feeder detection. Hence, zero sequence current magnitude in the transient region is a selective indicator for faulty feeder detection [4]. High magnitude of earth fault current flows in the cabled system, due to the capacitive currents of underground cables, provides a reliable steady-state faulty feeder selection method. However, hazardous over-voltages are observed on the isolated distribution systems [5]. To reduce over-voltages and earth fault current magnitude, Peterson Coils have been used for compensating capacitive currents of the cables [16]. Earth fault current magnitude is decreased. Low-level earth fault current provides service continuity of the system during single line to earth faults in compensated networks [17]. However, second earth fault may be triggered in the system. Thus, single line to earth fault must be isolated from the system as soon as possible. Low-level earth fault currents in the steady-state region leads to transient region-based faulty feeder selection algorithms to be developed.

TABLE I

USEFUL SUMMARY FOR SOME OF FAULTY FEEDER SELECTION STUDIES IN THE LITERATURE FOR COMPENSATED NETWORKS.

Paper	Proposed Method	Network Configuration	Line Configuration	Simulation Environment	Recorded Data?
[3]	Misoperation analysis	22 kV Δ/Y with 2 PFN.	Variable between 10 and 50 km mixed.	PSCAD	✓
[6]	Earth Capacitance Estimation	20 kV Δ/Y with 5 PFN.	184 km OHL	EMTP ATP-Draw	✓
[7]	Determine Transient Factor	10 kV Y/Δ with 5 PFN.	85 km OHL	RTDS	✓
[8]	Skewness feature of transient zero sequence current	10.5 kV Y/Δ with 4 PFN.	34 km OHL and 6 km cable	MATLAB	✓
[9]	Charge–voltage relationship	22 kV Y/Y with 3 PFN.	Approximately 121 km OHL densed. No detailed information	—-	✓
[10]	Wavelet Transform	10 kV Y/Δ with 8 PFN.	95 km OHL	EMTP	—
[11]	Using additional criteria	22 kV Δ/Y with 2 PFN.	50 km OHL and 10 km cable.	PSCAD	✓
[12]	Hilbert-Huang Transform	11 kV Δ/Y with 5 PFN.	57 km OHL and 25 km cable.	MATLAB	—
[13]	Traveling Wave	35 kV Y/Δ with 3 PFN.	40 km OHL	PSCAD	✓
[14]	Improved Hausdorff Distance Algorithm	10 kV Y/Δ with 5 PFN.	41 km OHL and 11 km cable.	PSCAD	✓
[15]	Active Energy Signal	12 kV Δ/Y with 3 PFN.	No detail information	EMTP ATP-Draw	✓

OHL: Overhead Line. PFN: Parallel Feeder Numbers. RTDS: Real Time Digital Simulator. PSCAD:Power System Computer Aided Design.

Table 1 summarizes different transient based algorithms for faulty feeder selection techniques in compensated networks. In [6], transient estimation for earth capacitance is carried out. In [7] transient factor is determined based on the compensation factor of Peterson Coil. Thus, faulty feeder is selected on 10 kV distribution networks. Using the skewness feature of transient zero sequence current signals of each feeder, faulty feeder selection is proposed in [8]. Utilizing charge-voltage relationship in transient region fault feeder is identified in [9]. The other methods such as; Wavelet Transform [10], Additional Criteria by using trapezoidal integration [11], Hilbert-Huang Transform [12], Traveling Wave [13], Improved Hausdorff Distance [14] provide selective faulty feeder detection in compensated networks. The methods depicted in Table 1 may suffer from the application on a real distribution network or request additional protection devices.

As depicted in Table 1, different simulation environments are used in the studies to simulate transient behavior of the earth faults. The recorded data is also used for the validation of the results in some studies. When the line structure is examined, it is seen that the considered cases in the literature mainly dealt with OHL dominated networks. However, it should be appreciated that usage of OHLs are not possible in metropolitan cities where underground cables are, extensively, used. Capacitive current of the underground cables causes misselection of faulty feeder in compensated networks [3], [11], [15].

Examined studies in Table 1 deal with networks that are designed with the intention of being compensated. However, increasing capacitive currents mainly due to the high penetration of underground cables, lead to a normal network behaving like a compensated network. Therefore, the network resonates unintentionally. Such networks are generally designed for limiting earth fault current magnitudes via grounding transformer or inductance. Therefore, it is not desired to operate under fault as in compensated networks. Nevertheless, the inductive characteristics of grounding transformers and capacitive currents of underground cables resonate with each other in the faulty feeder. Hence, zero sequence current magnitude in the faulty feeder is lower than the healthy feeders which leads to maloperation of non-directional earth fault (51N) protection. Parametric analysis of this phenomenon is investigated in [18]. Published field records show that higher zero sequence current may flow in healthy feeders than the faulty line [19]. By parametric analysis and field records, it can be concluded that zero sequence current based fault feeder selection methods may not be adequate. Directional earth fault protection may provide selective protection against such system. However, zero sequence based directional protection (67N) may be ineffective in compensated networks due to the fact that capacitive currents distort the directionality function [8]. This phenomenon is also discussed in Section III of this paper.

The adverse effect of the phase-to-earth capacitance in zero sequence equivalent circuit may be eliminated by using transient negative sequence component. Accordingly, this study proposes a transient negative sequence current based faulty feeder selection method. For this purpose, 151-node distribution network is selected for the faulty feeder selection analysis. Single line to earth fault simulations is carried out using ATP/EMTP (Alternative Transient Program/Electro Magnetic Transient Program) software. Effects of different fault inception times, fault resistance and capacitive imbalance of the system are also examined. Simulation results clearly show faulty feeder selection can be made using transient negative sequence current. Transient negative sequence current provides an effective solution against unintentional resonance problems in highly cabled distribution networks.

Thanks to the abilities of the existing modern relays used already in the field, the negative sequence logic can be implemented [20],[21]. Field tests of the proposed method will be conducted in the future works.

The remainder of this paper is organized as follows, Section II provides a deep analysis of false trips and unintentional resonance problems on the network based on the zero sequence current. The reason for using transient negative sequence current is demonstrated in Section II. Section III presents shortcomings of the classical 51N and 67N protection techniques in unintentional resonance networks. The application of transient negative sequence current based method is also presented in Section III. The results are discussed in the conclusion.

II. False Trip in Unintentionally Resonated Distribution Networks

Zero sequence current is a common indicator for earth fault relay setting against single line to earth faults. Low resistance earthed distribution networks with fully OHLs have simple protection methods. High magnitude zero sequence currents are seen in the faulty sections. The faulty feeder is easily detected. There is no need for complex algorithms. However, in underground cabled distribution networks, zero sequence current circulates both faulty and healthy sections during single line to earth faults [22]. Unnecessary isolation of healthy sections may occur in fault clearing processes depending on the earth fault relay settings or protection strategies implemented on the system [23], [24].

Figure 1a shows zero sequence equivalent circuit for radial distribution networks with two outgoing parallel feeders. For the fault at marked on Figure 1a, only relay $R_{1,1}$ should generate fault signal. In any case, $R_{2,1}$ should not generate any fault signals. As seen in Figure 1a, due to the phase-to earth capacitance of the underground cables, relay $R_{2,1}$ sees zero sequence current magnitude named as $I_{0,H,R}$. Relay $R_{1,1}$ sees zero sequence current magnitude named as $I_{0,F,R}$.

According to the direction of the zero sequence current and topology of the network, SSZCC can be calculated as given in Equation (1). Derivation of the equations are available in Appendix A.

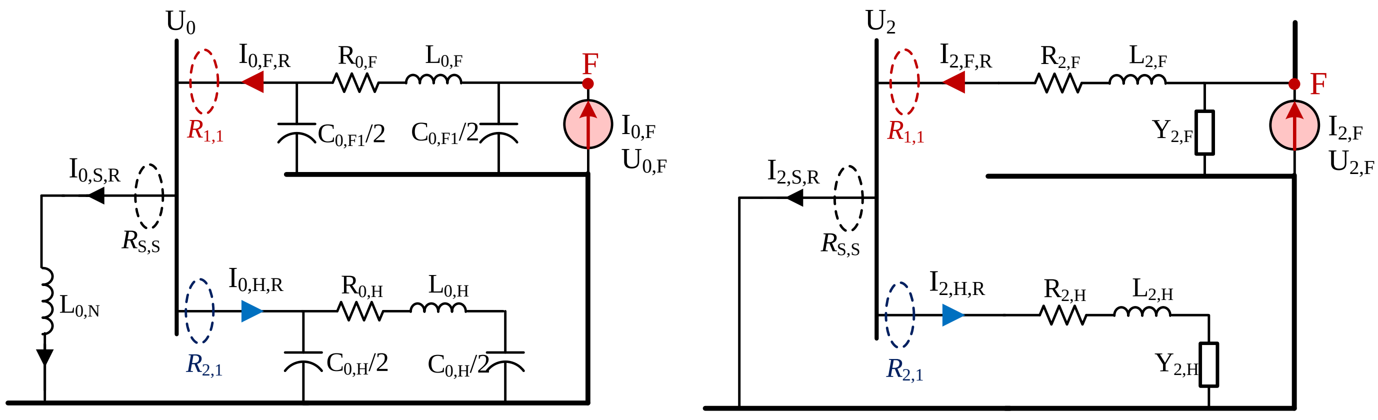
$$SSZSCC = \begin{cases} \vec{I_{0,F}} = \frac{E}{R_{0,F}+j\omega L_{0,F}+\left(\frac{1}{j\omega 3L_{0,N}}-j\omega 3C_{0,T}\right)^{-1}} \\ \vec{I_{0,F,R}} = \vec{I_{0,F}} + \vec{I_{0,CF}} \\ \vec{I_{0,S,R}} = \vec{I_{0,F,R}} + \vec{I_{0,H,R}} \\ \vec{I_{0,H,R}} \simeq \frac{U_0}{XC_{0,H}} \\ C_{0,T} = C_{0,H} + C_{0,F} \end{cases} \tag{1}$$

It is worth mentioning that SSZSCC equation is valid for OHLS. However, the magnitude of $I_{0,H,R}$ may not have higher magnitude to generate tripping signal.

Underground cable usage causes an increase in the magnitude of $I_{0,H,R}$. Due to the capacitive current feedback from the healthy feeder, the highest zero sequence current magnitude is seen in the faulty feeder. However, mentioned inference is acceptable for isolated and resistance earthed systems. Zero sequence current magnitudes of the faulty feeder have a different tendency in compensated networks or earthed trough grounding transformers. As seen in the SSZSCC equations, parallel connection of $C_{0,T}$ and $L_{0,N}$ leads to reducing of the $\vec{I_{0,F}}$ magnitude which allows the network to operate under faults. Therefore, it can be preferred by network operators. Preference can be applied in networks with overhead lines or cables with short distances because high magnitude of earth fault current will not be seen in the healthy feeders. However, in large networks with long cable feeders $I_{0,H,R}$ may be greater than $I_{0,F,R}$. Faulty feeder selection based on zero sequence current magnitude failed during the resonance condition. Worse, even though the network is not designed to be compensated, unintentional resonance may occur due to the feeder topology in the usage of particular grounding transformers. Figure 2 shows zero sequence current magnitudes variation of fault point, faulty feeder and healthy feeders in an exemplary distribution network. Distribution network consists of six radial parallel feeders. For simplicity, the length of each feeder has been increased evenly. This particular network has 33 Ω grounding transformer. Increasing feeder lengths results in decreasing zero sequence current magnitude in faulty feeder as expected. Decrement is not linear due to the capacitive current of underground cables. The decrease continues until approximately 60 A. After that point, zero sequence current magnitude increases with the increase of feeder length. From the point of view of healthy feeders, zero sequence current magnitude continuously increases. It is concluded that unintentional resonance occurs when the total cable length used in the distribution network is between 100 and 120 kilometers. In this type of distribution networks, steady-state-based faulty feeder selection methods fail.

Figure 1 must be considered as an RLC circuit. Therefore, transient behaviors of the radial distribution can be obtained as a set of differential equations [8], [25]. Transient Zero Sequence Current Characteristic (TZSCC) for Figure 2 is given in Equation (2). Detailed information about the derivation of the equations can be found in Appendix B. TZSCC have been used for detecting faulty feeder in compensated networks. Capacitive current of cables affects the performance of the TZSCC based faulty feeder selection algorithms. Reference [3] shows that the misoperation is inevitable in cabled networks. Similarly, Reference [11] represents the necessity of additional criteria to improve TZSCC based algorithms in the compensated distribution network. In the field, distribution networks may have mixed structures, including overhead lines and underground cables. During single phase to earth fault in the OHLs dense feeder, transient zero sequence currents in cabled healthy feeders may be higher than the faulted one as reported in [15].

$$TZSCC = \begin{cases} i_{0,H,R} = C_{0,H}\frac{du_0}{dt} \\ i_{0,F,R} = i_{0,S,R} + C_{0,T}\frac{du_0}{dt} \\ u_0 = L_{0,N}\frac{di_{0,S,R}}{dt} \\ u_{0,F} - u_0 = i_{0,S,R} + R_{0,F}C_{0,T}\frac{du_0}{dt} \\ i_{0,F,R} = i_{0,S,R} + L_{0,N}C_{0,T}\frac{d^2 i_{0,S,R}}{dt^2} \end{cases} \tag{2}$$



(a) (b)

Fig. 1. Symmetrical component equivalent circuit for radial distribution system with two feeders a) zero sequence equivalent circuit b) negative sequence equivalent circuit.

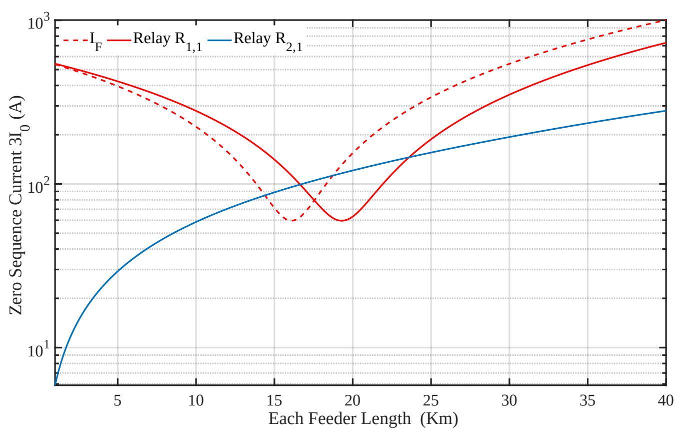


Fig. 2. SSZSCC of distribution networks with six parallel feeders.

The main disadvantage of both SSZSCC and TZSCC based faulty feeder algorithms is the phase to earth capacitance of the underground cables in the zero sequence equivalent circuit. Figure 1b shows the negative sequence equivalent circuit of the radial distribution network. Mainly, positive and negative capacitances have high magnitude impedance compared to the line impedance. They can be neglected for the earth fault analysis. Therefore, as seen in Figure 1b, phase-to-phase capacitance is not addressed on the equivalent circuit. Therefore, transient negative sequence based faulty feeder selection method needs to be used due to its immunity to the phase to earth capacitance. Negative sequence current can be calculated by the digital relays without using any voltage transformer. The calculation of the negative sequence current is given in Equation (3). Where F_s is the sampling frequency of the relay, f is the power frequency.

$$I_2(n) = \frac{1}{3}(I_A(n) + I_B(n - \frac{F_s}{3f}) + I_C(n - \frac{2F_s}{3f})) \quad (3)$$

It is worth mentioning that the accuracy and tolerance limit of the negative sequence calculation expressed by Equation (3) varies according to the voltage unbalance. Further, natural frequency variations may also affect measurement accuracy. Both problems will be dealt with in the future paper for the field application of the proposed technique.

The negative sequence current calculation is immune to the adverse effect of phase-to-ground capacitance. However, it would be affected by the unbalance in the load current. Load unbalancing is not sensed by the upstream relays due to the delta/star connection of the LV transformers. Zero sequence circuit breaks zero sequence current on the LV side and does not transfer on the MV side. However, the relays see negative sequence currents on the MV side in pre-fault condition. Although negative sequence currents may be influenced by the presence of the load unbalancing, recent publications are encouraging the use negative-sequence component for the protection of the distribution networks [26], [27]. Therefore it is worth exploring the possibility of using transient negative sequence current.

III. Faulty Feeder Selection on 151-Nodes Distribution Networks: Case Study

Two different neutral earthing treatment is used in Turkey. In 154/33 kV Y/Y substations, secondary side of power transformer earthed through 20Ω resistance. Underground cables positively effect the faulty feeder selection method due to the fact that capacitive current flows through fault point. Hence, zero sequence current magnitude in faulty feeder increases [28].

400/33 kV Y/Δ substations have earthing transformer on low voltage side in Turkey. Highly inductive nature of the earthing transformer may cause unintentional resonance. Therefore, topology of the distribution network plays a critical role in unintentional resonance.

Figure 3 shows line configuration of the 151-node distribution network. Topology has seven outgoing feeders. The length of the feeders is given in Figure 3 as meters. Feeders' relays are also illustrated on the Figure 3. Total length of the underground cables is 112 km. 240 mm^2 single core XLPE in flat formation cable is used [29]. Using Figure 3 ,

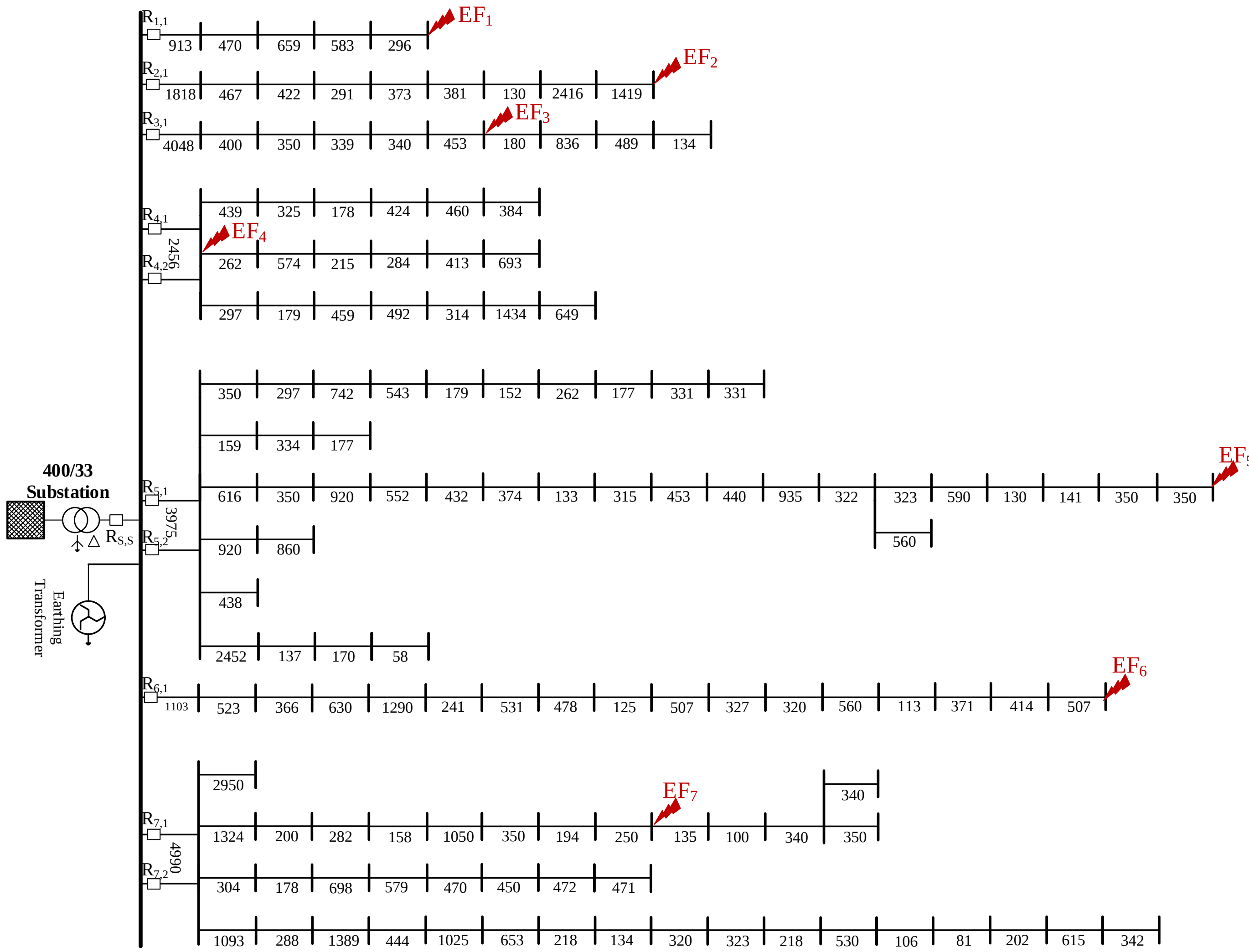


Fig. 3. 400/33 kV Y/Δ 151-node distribution network for single line to earth fault analysis.

TABLE II
ZERO SEQUENCE CURRENT MAGNITUDE SEEN BY THE RELAYS FOR THE DIFFERENT FAULT LOCATIONS.

	Underground Cable (240 mm^2 single core XLPE)							Overhead Line (Pigeon Conductor)						
Relay	EF_1	EF_2	EF_3	EF_4	EF_5	EF_6	EF_7	EF_1	EF_2	EF_3	EF_4	EF_5	EF_6	EF_7
$R_{1,1}$	64.30	17.42	17.42	17.48	17.41	17.39	17.40	530.32	0.19	0.20	0.22	0.18	0.19	0.19
$R_{2,1}$	46.11	80.32	46.00	46.15	45.97	45.91	45.95	0.55	479.47	0.52	0.57	0.48	0.50	0.51
$R_{3,1}$	45.21	45.11	79.70	45.25	45.07	45.02	45.05	0.57	0.52	499.52	0.59	0.50	0.51	0.53
$R_{4,1}$	40.53	40.44	40.44	53.83	40.41	40.36	40.39	0.49	0.44	0.46	275.58	0.42	0.44	0.45
$R_{4,2}$	40.53	40.44	40.44	53.83	40.41	40.36	40.39	0.49	0.44	0.46	275.58	0.42	0.44	0.45
$R_{5,1}$	76.84	76.66	76.65	76.90	86.25	76.55	76.57	0.90	0.82	0.85	0.94	231.36	0.82	0.84
$R_{5,2}$	76.84	76.66	76.65	76.90	86.25	76.55	76.57	0.90	0.82	0.85	0.94	231.36	0.82	0.84
$R_{6,1}$	44.46	44.36	44.36	44.50	44.33	79.04	44.31	0.57	0.51	0.53	0.59	0.49	477.73	0.52
$R_{7,1}$	90.30	90.09	90.08	90.37	90.02	89.91	98.93	1.10	1.00	1.04	1.14	0.96	0.99	245.76
$R_{7,2}$	90.30	90.09	90.08	90.37	90.02	89.91	98.93	1.10	1.00	1.04	1.14	0.96	0.99	245.76

it can be predicted that there may be a resonance problem in the network.

Originally, distribution systems are designed to limit the single line to earth fault current magnitude up to 600 A. Earth fault current magnitude is expected to decrease due to the limiting effect of the reactance in the grounding transformer. However, this assumption is only valid for the topology equipped with full OHLs or short distanced cable feeders. Extensive cable usage may cause unintentional resonance on the system. Eventually, false trip occurs on the healthy feeders.

Some assumptions have been made for single line-to-earth fault analysis. As the permanent earth fault is the main

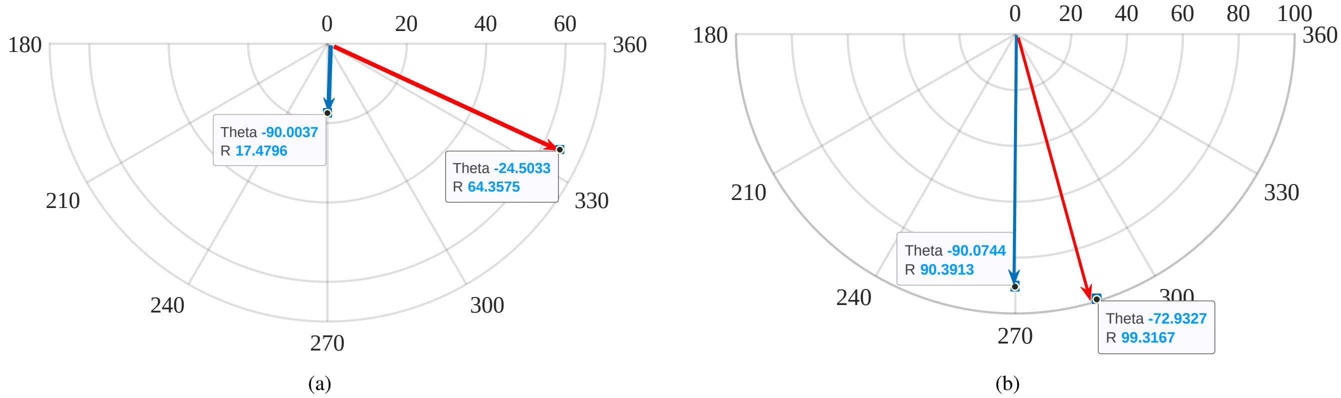


Fig. 4. Directional earth fault protection applying on 151-nodes distribution networks a) Feeder One b) Feeder Seven

concern, the underground cables' insulation level is considered equal. Therefore, cable conductance is neglected. Both-ends grounding practice is applied on the sheath of cables. Load currents effect is also neglected due to the delta connection of the loads. Effect of the load unbalance will be studied in the future work.

To show the shortcomings of the traditional 51N and 67N protection, they are applied on the 151-node distribution network. For the performance evolution of 51N, seven different single line to earth faults are simulated. Therefore, all feeders faults can be presented on the 151-nodes distribution network. Fault locations are marked on the figure. For each fault location case; zero sequence current magnitudes are obtained as RMS in steady-state region in all relay locations. Earth fault simulations are repeated for OHL and cable cases.

Table 2 lists zero sequence current magnitudes seen by the relays for the different fault locations. As seen in Table 2, zero sequence current magnitudes are reliable indicators for faulty feeder selection in OHLs. For the fault at EF_1 Relay $R_{1,1}$ sees 530.32 A. Other relays see a negligible level of zero sequence current. Therefore, faulty feeder identification successfully preserves the selectivity via 51N algorithm. No false trip occurs on the healthy feeders due to the very low level zero sequence current with the setting of the pick-up level i.e. 10 A.

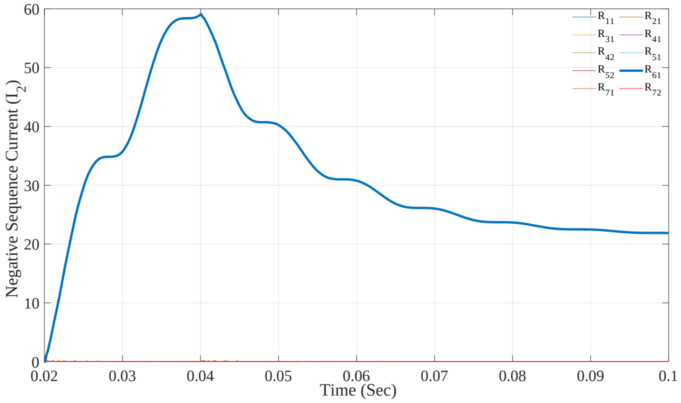
Unintentional resonance occurs for the cabled cases. Zero sequence current resonating in the fault path causes zero sequence current magnitude less reliable for the selective faulty feeder detection. It is expected that the highest zero sequence current is seen by the Relay $R_{1,1}$ in the same earth fault location (EF_1). On the contrary, Relay $R_{5,1}$-$R_{5,2}$ and $R_{7,2}$-$R_{7,2}$ see higher zero sequence current magnitudes than the faulty feeder relay $R_{1,1}$. During monitoring of the highest zero sequence current, Feeder Seven considered as faulty and isolated from the system. Un-selective isolation continues at other fault points except EF_7. Since Feeder Seven is the longest feeder, the highest zero sequence current is seen in Feeder Seven. Therefore selective faulty feeder selection is made only for the EF_7. Increasing pick-up current level will not solve the problem.

67N protection is used in field applications to protect MV feeders. Classical 67N protection uses zero sequence current angle of each feeder as an operating signal; zero sequence voltage of the common busbar is used as a reference. Selective protection is provided by directional discrimination in the resistively earthed system and isolated earthed system. However, in fully-compensated networks, DEF may not provide successful faulty feeder selection [8]. Similarly, the unintentional resonance problem negatively affects the performance of DEF protection. Figure 4 shows a zero sequence polar diagram. Earth fault has occurred for all 151-nodes. Relay $R_{1,1}$ on Feeder One, which is the shortest and Relay $R_{7,1}$ on Feeder Seven which is the longest, have been selected to compare DEF selectivity performance. The red vector represents when the fault occurred in the relay zone, blue vector represents when the fault occurred out of the relay zone. All vectors are drawn for the zero sequence voltage angle of the common busbar as a reference. For Feeder One, sufficient angle difference can be seen. Hence, DEF protection may provide selective solution. For Feeder 7, narrow angle difference is seen between faulty and healthy status. Considering angle measurement errors and safety factors, DEF protection fails to provide selective discrimination.

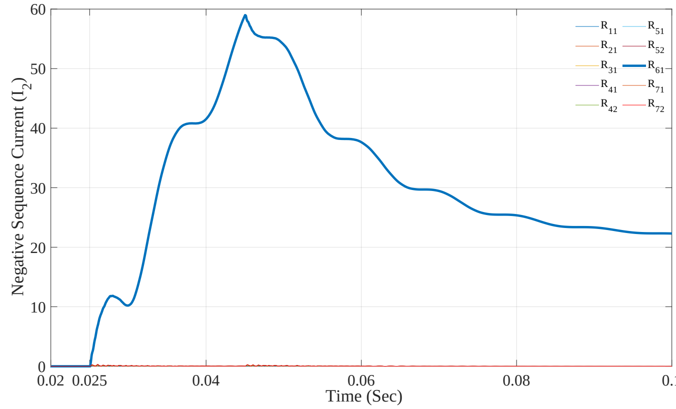
The proposed transient negative sequence based faulty feeder selection method is implemented on 151-nodes distribution network. Single line to earth faults in transient regime has occurred on the network. The phase current of each relay location is transferred to MATLAB. Signal processing is conducted in MATLAB Environment. For the calculation process of the transient negative sequence current of each relay locations, Moving Average Method is preferred. Moving Average Method has many advantages such as simple calculation process, highly durable against oscillations in the signal, easily applied in MATLAB-Simulink. Different parameters (fault inception angle, fault resistance, capacitive current imbalance) are considered in order to demonstrate the effectiveness of the proposed method.

A. Different Fault Inception Angles

In transient regime analysis, the angle of occurrence of the fault, that is, the fault inception time is a parameter that should



(a)



(b)

Fig. 5. Negative sequence current magnitude during single line to earth fault a) t=0.02 sec. $R_F = 100\Omega$ b) t=0.025 sec. $R_F = 100\Omega$

be examined. Figure 5 shows different negative sequence current waveforms of each relay with different fault inception angle scenarios. For different fault inception times EF_6 earth fault is simulated. EF_6 should be cleared with only tripping signal of relay $R_{6,1}$. In Figure Figure 5.a, single line to earth fault occurred at the t=0.02 seconds through fault resistance which value is 100Ω. Faulty feeder relay $R_{6,1}$ has the only negative sequence current change after the fault inception in the transient region. Faulty feeder can be detected in the half cycle of fault starting time by using Moving Average Method. Figure 5.b shows single line to earth fault occurred at the time t=0.025 seconds. Sudden changes are observed in the faulty feeder. It is concluded that, for the different fault inception times transient negative sequence current magnitudes allow easy detection of faulty feeder on network.

B. Capacitive Current Imbalance of Underground Cables

Capacitive imbalance jeopardizes many transient and steady-state zero sequence current based methodologies. Accordingly, the effectiveness of the negative sequence current based faulty feeder selection against capacitive imbalance is investigated. In order to examine the effect of capacitive imbalance in detail, different ratios of capacitive imbalances are created in different feeders on the 151-Nodes distribution network. The value of the capacitive current imbalance is selected as 1%, 5% and 10% of the capacitive current value seen at the feeder's head in normal and no load condition.

Table III gives negative sequence current magnitudes for both faulty and healthy feeders with different ratios of capacitive imbalance. RMS values are obtained by using Moving Average Method in MATLAB. Due to the very low level of negative sequence currents in the balanced feeders their values are not given in Table III. For example, single line to ground fault occurred at the end of the Feeder One, relay $R_{1,1}$ sees 21.80A negative sequence current. On the contrary, $R_{5,1}$ and $R_{5,2}$ see 0.48A negative sequence current in the unbalanced feeder.

As expected, increasing capacitive current imbalance increases the negative sequence magnitude in the unbalanced feeder. In addition, the negative sequence current magnitudes in the faulty feeder decreases. However, in any case, there is a difference in the magnitude that can be distinguished between the faulty feeder and the healthy feeder. It should be underlined that 10% capacitive current imbalance is not common in field applications. As it can be clearly seen from Table III, the transient negative sequence current magnitudes provide selective results against capacitive current imbalance. Therefore, it can be concluded that the transient negative sequence currents are more reliable than the transient zero sequence currents.

C. Different Fault Resistance Effect

Both steady state and transient zero sequence based fault feeder selection algorithms are affected by the fault resistance. Thus, parametric analysis of the fault resistance effect is analyzed in order to demonstrate the effectiveness of the proposed transient negative sequence current method. Earth fault is created in the first feeder (EF_1) and the negative sequence currents are obtained from the relay positions for different fault resistances using Moving Average Method. Increasing fault resistance causes decreasing negative sequence current magnitude. Still, transient change is observed only in faulty feeders as seen in Table IV. Differences between faulty and healthy sections are considerable enough to detect faulty sections and prevent false tripping in healthy sections. Therefore by using transient negative sequence current magnitude, high impedance fault can easily be detected.

D. Mixed-Structure of MV Lines

151-nodes distribution network is located out of the resonance zone when mixed feeder structures are used. For example, if feeder five is constructed with full OHLs total length of the cables is 87 km. For the new topology arrangement, zero sequence current magnitude is higher than the healthy feeders. Therefore, steady-state zero sequence current magnitude based methods may be preferable to transient negative sequence current magnitude methods due to the simplicity in application on the field. Hence, the effects of the mixed feeder usage are excluded from the

TABLE III
CAPACITIVE IMBALANCE EFFECTS ON THE FAULTY FEEDER SELECTION

Relay	Faulty Feeder- Imbalanced Feeder- Capacitive Imbalance Ratio					
	$F_3/F_7/1\%$	$F_3/F_7/5\%$	$F_3/F_7/10\%$	$F_1/F_5/1\%$	$F_1/F_5/5\%$	$F_1/F_5/10\%$
$R_{1,1}$	-	-	-	21.80	21.11	20.37
$R_{2,1}$	-	-	-	-	-	-
$R_{3,1}$	22.01	21.19	20.29	-	-	-
$R_{4,1}$	-	-	-	-	-	-
$R_{4,2}$	-	-	-	-	-	-
$R_{5,1}$	-	-	-	0.48	1.10	1.88
$R_{5,2}$	-	-	-	0.48	1.10	1.88
$R_{6,1}$	-	-	-	-	-	-
$R_{7,1}$	0.59	1.35	2.31	-	-	-
$R_{7,2}$	0.59	1.35	2.31	-	-	-

TABLE IV
FAULT RESISTANCE EFFECT ON THE FAULTY FEEDER SELECTION FOR THE FAULT AT EF_1

Relay	Fault Resistance (Ω)						
	1	10	20	200	400	800	1000
$R_{1,1}$	34.64	31.55	29.44	17.00	11.77	7.29	6.11
$R_{2,1}$	0.29	0.23	0.23	0.22	0.22	0.22	0.22
$R_{3,1}$	0.30	0.24	0.24	0.23	0.23	0.22	0.22
$R_{4,1}$	0.26	0.20	0.20	0.19	0.19	0.19	0.19
$R_{4,2}$	0.26	0.20	0.20	0.19	0.19	0.19	0.19
$R_{5,1}$	0.48	0.38	0.38	0.36	0.36	0.36	0.36
$R_{5,2}$	0.48	0.38	0.38	0.36	0.36	0.36	0.36
$R_{6,1}$	0.30	0.24	0.24	0.23	0.22	0.22	0.22
$R_{7,1}$	0.59	0.47	0.46	0.44	0.44	0.43	0.43
$R_{7,2}$	0.59	0.47	0.46	0.44	0.44	0.43	0.43

investigated parameters. However, mixed-structure of MV lines in unintentional resonance will be studied in the future works.

E. Load Unbalancing of MV Lines

In the field, LV distribution networks may have many lateral and branches due to their nature. Single phase loads can be fed from the three phase lines. Zero sequence current unbalancing does not transfer on the MV side due to the delta/star connection of LV transformers which are extensively used. The same observation is not valid for the negative sequence currents. Unbalanced loads cause negative sequence current in pre-fault conditions. The negative sequence pick-up current value of the unbalanced feeder might be increased or the zero sequence voltage of the common busbar can be used to prevent the false signal which is generated by the unbalanced feeder. Further parametric analysis will be conducted in the future works. Simulation results presented in Figure 4, Table III and Table IV explicitly show that transient negative sequence current magnitude can be considered as a solution method for the unintentionally resonated cabled distribution networks. Zero sequence current is prone to misoperation due to the capacitive imbalance and capacitive current. On the contrary, the negative sequence current is not affected by the relevant parameters in the transient regime. Also, the negative sequence component is more durable against the fault resistance parameter, which causes problems in zero-sequence component-based protection methods. In each scenario, the faulty feeder is selectively detected. Field tests of this proposed method will be carried out in future studies.

IV. CONCLUSIONS

Transient methods for faulty feeder selection studies are continuously developing in compensated networks. Zero sequence current based transient methods are affected by the capacitive imbalance of the system, capacitive currents of the underground cables and fault resistance. Moreover, capacitive currents of underground cables are not negligible in modern distribution systems

Extensive cable usage in metropolitan cities is inevitable due to space, safety and security constraints. Extensive cable usage causes unintentional resonance in inductance earthed distribution networks. Since the protection relays and its settings of the system are not designed against unintentional resonance problem, faulty feeder may not be detected. EMTP simulations show that zero sequence current magnitudes of healthy feeders are higher than the faulty feeder. This contrast in magnitude causes the healthy feeder to be isolated incorrectly which is known as false tripping.

This work proposed transient negative sequence current based faulty feeder selection methods. Using transient negative sequence currents faulty feeder can be selected correctly. Analyses are also presented by considering different parameters which affect the performance of the transient zero sequence current based algorithms.

In this work, the real 151-Nodes distribution system is modeled in ATP-EMTP. Transient earth fault simulations are carried out with different scenarios. Simulation results demonstrate that negative sequence current in transient region is a reliable indicator for selective faulty feeder detection. The presence of cables does not effect negative sequence current selectivity performance. Even, in capacitive current imbalances, transient negative sequence provides preferable selectivity performance. As a future work, real data taken from the field will be used in order to improve the proposed method. Further parametric analysis will also be carried out in the future works.

V. Appendix

A. Steady-State Zero Sequence Current Characteristics of The Radial Distribution Network

SSZSCC can be derived as follows. Total phase-to-earth capacitance of the networks is sum of the faulty and healthy phase-to-earth capacitance as indicated in Equation (4).

$$C_{0,T} = C_{0,H} + C_{0,F} \tag{4}$$

In zero sequence equivalent circuit, there is parallel connection between $C_{0,T}$ and $L_{0,N}$. Zero sequence current magnitude of the fault point can be calculated in Equation (5).

$$\vec{I_{0,F}} = \frac{E}{R_{0,F} + j\omega L_{0,F} + \left(\frac{1}{j\omega 3L_{0,N}} - j\omega 3C_{0,T}\right)^{-1}} \tag{5}$$

Between fault point and feeder-head capacitive current of faulted part is circulated. This phoneme states as indicated in Equation (6).

$$\vec{I_{0,F,R}} = \vec{I_{0,F}} + \vec{I_{0,CF}} \tag{6}$$

During single line to earth, common busbar has zero sequence voltage. Neglecting series impedance of the healthy line. Calculation of the zero sequence current magnitude in healthy feeder is given in Equation (7).

$$\vec{I_{0,H,R}} \simeq \frac{U_0}{XC_{0,H}} \tag{7}$$

By applying Kirchhoff Current Law to Equation (6) and Equation (7). Equation (8) has been formed.

$$\vec{I_{0,S,R}} = \vec{I_{0,F,R}} + \vec{I_{0,H,R}} \tag{8}$$

B. Transient Zero Sequence Current Characteristics of The Radial Distribution Network

Figure 1 can be considered as a parallel RLC circuit for simplicity to calculation. Capacitance of the healthy line is discharged on the common busbar as given in Equation (9).

$$i_{0,H,R} = C_{0,H}\frac{du_0}{dt} \tag{9}$$

$L_{0,N}$ is earthed to ground through common busbar.Thus, $i_{0,S,R}$ flows to the ground through $L_{0,N}$. Therefore, Equation (10) can be derived.

$$u_0 = L_{0,N}\frac{di_{0,S,R}}{dt} \tag{10}$$

By applying Kirchhoff Current Law to Equation (9) and Equation (10), Equation (11) has been formed.

$$i_{0,F,R} = i_{0,S,R} + C_{0,T}\frac{du_0}{dt} \tag{11}$$

Zero sequence voltage difference between feeder-head and fault point can be calculated as indicated in Equation (12).

$$u_{0,F} - u_0 = i_{0,S,R} + R_{0,F}C_{0,T}\frac{du_0}{dt} \tag{12}$$

Substitute the Equation (9) into the Equation(11). Equation (13) is derived.

$$i_{0,F,R} = i_{0,S,R} + L_{0,N}C_{0,T}\frac{d^2 i_{0,S,R}}{dt^2} \tag{13}$$

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