

A Novel Application of Network Equivalencing Method in Time Domain to Precise Calculation of Dead Time in Power Transmission Title

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Abstract—Various studies have showed that about 90% of single line to ground faults occurred on High voltage transmission lines have transient nature. This type of faults is cleared by temporary outage (by the single phase auto-reclosure). The interval between opening and reclosing of the faulted phase circuit breakers is named “Dead Time” that is varying about several hundred milliseconds. For adjustment of traditional single phase auto-reclosures that usually are not intelligent, it is necessary to calculate the dead time in the off-line condition precisely. If the dead time used in adjustment of single phase auto-reclosure is less than the real dead time, the reclosing of circuit breakers threatens the power systems seriously. So in this paper a novel approach for precise calculation of dead time in power transmission lines based on the network equivalencing in time domain is presented. This approach has extremely higher precision in comparison with the traditional method based on Thevenin equivalent circuit. For comparison between the proposed approach in this paper and the traditional method, a comprehensive simulation by EMTP-ATP is performed on an extensive power network.

Keywords—Dead Time, Network Equivalencing, High Voltage Transmission Lines, Single Phase Auto-Reclosure.

I. INTRODUCTION

TODAY'S, general networks are used by many countries to achieve maximum efficiency and improve the quality of operation in power systems. Also in some cases, the network is developed to interconnected or intercontinental network. However if a fault occurs on an important Power Transmission Line (PTL) and the faulted part is not disconnected from the network rapidly, it can impress other countries' networks. So, if a fault occurs on an important PTL, it is necessary to isolate the line from the network as soon as possible to prevent damages caused by short circuit currents [1]-[3]. Moreover, disconnecting the PTL from the network (even for a short time) may cause to serial outage of PTLs and general extinguishing due to stress in power system. Therefore, the only alternative is to use Single Phase Auto-Reclosure (SPAR) with the other protection systems. The programming of SPAR is so that after opening the Circuit Breakers (CBs), faulted phase relay is activated and the reclosing command is sent for the CBs after a short time. If the fault is transient, line returns to its normal status, otherwise the faulted part is disconnected from the network again. Although intelligent type of these relays is available, in many PTLs, unintelligent relays are

used. In unintelligent relays, whether fault is transient or permanent, faulted phase is returned to the circuit by the SPAR with a constant time delay. Adjustment of these relays is based on off-line calculation of dead time.

Dead time cannot be less than a specified time. Reclosing of faulted phase CBs is possible just when the ionized air at the fault location achieves its lost isolating property. If this minimum time (down limit of dead time) is not considered, the fault is established at the same location after the CB reclosing. The dead time also cannot be more than a specified value. This time value known as upper limit of dead time is determined by the line stability limit. If this dead time is estimated incorrectly, it can be a serious problem for the power system. So, for adjustment of SPAR, dead time should be calculated precisely.

In popular approach used by the most operators for dead time calculation, under study PTL is modeled in the software with complete details and the equivalent Thevenin or Norton circuits are considered for remained parts of the system. But it should be noted that traditional equivalent Thevenin or Norton circuits are not suitable for transient studies, because wideband frequency spectrum affects on achieved results. Hence, in this paper an equivalencing method in time domain has been used to precise calculation of dead time with replacing traditional Thevenin and Norton equivalent circuit. So SPARs can be adjusted accurately and this increases the stabilities of PTLs and power network.

II. EXTERNAL NETWORK EQUIVALENCING IN TIME DOMAIN

Power networks can be simulated in time domain with high precision and quality in transient studies. These studies need accurate details from the used models in under study power system. Usually, details of models used in the whole system elements are too much due to information content and time of the system response. Therefore, study on power system will be difficult or even impossible. For instance, switching, presence of transient faults in the network and dynamic analysis of AC/DC systems are some of these surveys. In such studies usually a large number of elements and corresponding models should be simulated in an extensive network and the software must be carried out, whereas the researcher usually is interested to analyze a small part of the network only (as the understudy PTL for dead time calculation). In such situations, using network equivalencing for remained parts of the system that are not considered, can decrease the system complexity and helps to get desire results faster. Various approaches for

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network equivalencing have been represented [4]-[15]. In this paper, an approach is proposed for precise calculation of dead time based on using of equivalencing in time domain [5] replacing Thevenin or Norton equivalent circuit. The resulted model is in the form of a Norton equivalent circuit consisting of the source, impedance and other supplementary elements corresponding to the network behavior in transient state. Network equivalence is achieved simply and can be simulated in EMTP-ATP environment easily.

III. DISCRETE MODEL OF THE EXTERNAL NETWORK IN THE SINGLE-CONNECTION MODE

Fig. 1 shows the under study system and the external system connecting only by a link. The main network is a part of the whole network and the purpose is to analyze and model all of its components in detail. However, the external network is part of the network which is added to the main network after specifying an equivalent circuit for it. It should be noted that although the internal signals are not of any importance to the researcher, the signal created between two networks' boundary is very important. So it is necessary for the proposed equivalent circuit to response to the main network motivations completely similar to the external network in a wide range of frequency bands.

The external network influence can be considered as an admittance function, $H(s)$, related to the voltage of the connection spot and the injected current to the connecting node of the two networks:

$$I(s) = H(s)V(s) = K \frac{N(s)}{D(s)} V(s) \quad (1)$$

$$N(s) = n_0 + n_1 s + \dots + n_p s^p \quad (2)$$

$$D(s) = d_0 + d_1 s + \dots + d_p s^p \quad (3)$$

$$\left(d_0 + d_1 \frac{d}{dt} + \dots + d_p \frac{d^p}{dt^p} \right) i(t) = K \left(n_0 + n_1 \frac{d}{dt} + \dots + n_p \frac{d^p}{dt^p} \right) V(t) \quad (4)$$

where k is a constant value representing efficiency constant in (1). Here, it is assumed that the number of zeroes is equal to the number of poles, without losing the generality of the transfer function [5]. When the Laplace variable s is replaced by d/dt , (1) turns to the time (4). This p^{th} - order differential equation can be converted to a linear differential equation by numerical methods like Euler method. First, variables i_1, \dots, i_p and V_1, \dots, V_p are defined as follows:

$$\frac{di}{dt} = i_1, \dots, \frac{di^p}{dt^p} = i_p \quad (5)$$

$$\frac{dv}{dt} = V_1, \dots, \frac{dv^p}{dt^p} = V_p \quad (6)$$

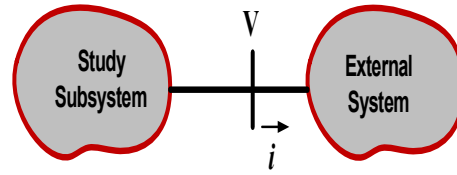


Fig. 1 Connection of the main network to the external network in a spot

The following differential equations are obtained by the Euler method:

$$i_{j+1}(t) = \frac{1}{\Delta t} [i_j(t) - i_j(t - \Delta t)], j = 0, 1, \dots, p-1, \quad (7)$$

$$i_0 = i$$

$$V_{j+1}(t) = \frac{1}{\Delta t} [V_j(t) - V_j(t - \Delta t)], j = 0, 1, \dots, p-1, \quad (8)$$

$$V_0 = V$$

where Δt is the integration interval. By substituting (7) and (8) in (4), (9) is achieved:

$$i(t) + a_1 i(t - \Delta t) + \dots + a_p i(t - P\Delta t) = g_0 V(t) + g_1 V(t) + \dots + g_p V(t - P\Delta t) \quad (9)$$

As the equivalent approach utilized in this paper estimates the values g_i, a_i directly, there is no need to calculate them in term of values d_i, a_i . These calculations clearly show that the differential equation in the form of (9) can be an appropriate representation of governing equations in the under study external network in a wide range of frequency bands. Meanwhile, the order p is specified by the researcher using the approach given in [5].

A. Model Assignment and Parameter Estimation

Equation (9) can be written as follows:

$$i(t) = -\sum_{k=1}^p a_k i(t - k\Delta t) + \sum_{l=0}^p g_l v(t - l\Delta t) \quad (10)$$

Indeed, (10) shows the presented model for equivalencing the external network. The model can be specified by obtaining the order p . As the frequency response of the external network is shown by the parallel and series resonances in the transfer function, the p order depends on the frequency range in which the presented model is valid and precise. Therefore, it is necessary to check not only the power frequency, but also the whole relevant frequency range in analyzing each phenomenon. Equation (10) describes the response of the external network to a voltage signal applied to the external network at the boundaries of two main and external networks.

In fact, this response is the injected current to the external network.

In order to describe the calculating method of coefficients g_i, a_i , it is assumed that voltage and current calculations in the boundary area of the two main and external systems are done by applying some sinusoid voltages to the external system in the permanent state by EMTP or any other software. While $i(k)$ and $v(k)$ are the injected current and the voltage of the boundary area at the k^{th} time step respectively, the matrix equation for N-P-1 time steps is presented as follows where N and P represent total sum of the time steps and the order of transfer function respectively :

$$Z = X.\theta \quad (11)$$

where,

$$Z^T = [i(N), i(N-1), \dots, i(P+1)] \quad (12)$$

$$\theta^T = [a_1, a_2, \dots, a_p, g_0, g_1, \dots, g_p] \quad (13)$$

$$X = \begin{bmatrix} i(N-1) & i(N-2) & \dots & i(N-p) & V(N) & V(N-1) & \dots & V(N-p) \\ i(N-2) & i(N-3) & \dots & i(N-p-1) & V(N-1) & V(N-2) & \dots & V(N-p-1) \\ \vdots & \vdots & & \vdots & \vdots & \vdots & & \vdots \\ i(P) & i(P-1) & \dots & i(P) & V(P+1) & V(P) & \dots & V(P) \end{bmatrix} \quad (14)$$

The value of Least-Squares Estimation (LSE) for the parameters of vector θ is given as:

$$\theta = (X^T.X)^{-1}.X^T.Z \quad (15)$$

As finding the inverse matrix of $X^T.X$ is difficult because of slow convergence, it is helpful to use numerical methods like QR analysis in calculation of vector θ .

B. Implementation of the Model in EMTP in Single Phase Modeling Mode

Assuming all the voltage and current values of the previous times i.e. $i(t-k\Delta t)$ and $V(t-k\Delta t)$, $k=1, \dots, p$ are accounted in the history h, (10) is rewritten. So the equation turns to the following equation:

$$i(t) = g_0 V(t) + \sum_{k=1}^p [g_k.V(t-k\Delta t) - a_k i(t-k\Delta t)] = g_0.V(t) + h \quad (16)$$

Equation (16) shows the discrete-time Norton equivalent circuit of Fig. 2.

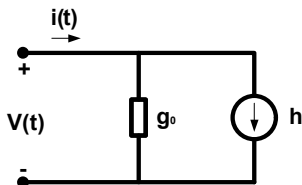


Fig. 2 Single phase discrete-time Norton equivalent circuit

The circuit of Fig. 2 shows the frequency dependent admittance of the external system in time domain. Thus the single phase equivalent circuit of the external system is achieved by adding the thevenin voltage of the system in series with Norton equivalent circuit of Fig. 2. The equivalent circuit has been shown in Fig. 3. The thevenin voltage of the external system is achieved by opening the circuit path of the external network at the boundary area with the main system considering all the sources of the external system in the permanent state.

It should be noted that at the time of connecting two main and external systems to each other, the current source h is zero and therefore the terminal voltage of the external system defined by $V_{th} - h / g_0$ will be equal to V_{th} . In order to avoid lengthening the paper, for more information about generalizing this method to the multi-connection network and three-phase system refer to the [5].

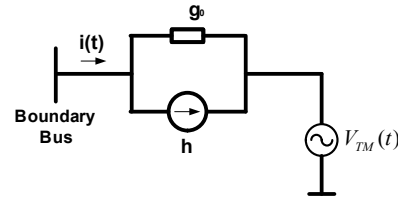


Fig. 3 The equivalent circuit of the external network in single mode

IV. SIMULATION AND RESULTS

For precise calculation of dead time, an extensive power network has been considered in Fig. 4. We have focused our studies on two PTLs, L1 and L2. L1 is a 320 km, 400kV PTL whereas L2 is 215 km, 230kV. Dead time will be calculated for each of these lines by two following methods. In the first method, under study line is considered and Thevenin equivalent circuit at two sides of given line is used for remained part of the network. It should be noted that in most references, this method is used for dead time calculation [16]-[18]. Then, this network that consists of the understudy PTL, two constant voltage source and impedances at two side of PTL, is simulated in EMTP-ATP. The Fault (including primary and secondary arc) is modeled based on [19].

In second method, the remaining part of the network is replaced by two equivalent circuits, using network equivalent approach in time domain. In this method, two equivalent circuits mentioned in section II are used at two sides of the PTL (required calculations for obtaining the equivalent networks are left to the reader). Then the network including the understudy PTL and two equivalent circuits is simulated in EMTP-ATP. The Fault is yet modeled based on [19].

A. Calculation of Dead Time Using Thevenin Equivalent Circuit

At first, L1 is modeled with Jmarti model and skin effect is considered. Positive and zero sequence resistance, inductance and capacitance of this PTL have been considered as follows:

$$\begin{aligned}
 R_1 &= 0.012526 \Omega/\text{km} & R_0 &= 0.04624 \Omega/\text{km} \\
 L_1 &= 0.8838 \text{ mH}/\text{km} & L_0 &= 2.6563 \text{ mH}/\text{km} \\
 C_1 &= 0.0126 \mu\text{F}/\text{km} & C_0 &= 0.0043 \mu\text{F}/\text{km}
 \end{aligned}$$

The corresponding impedances of the Thevenin equivalent circuit network at two sides of the PTL are shown in Table I. Also, under study network (involving L1) has been shown in Fig. 5. A transient Single Line to Ground (SLG) fault has been assumed in the middle of above PTL. Voltage waveform at the beginning of faulted phase has been shown in Fig. 6. It is evident from the figure that the SLG fault has been occurred at $t = 190$ msec and the CBs have disconnected faulted phase from the circuit at $t = 200$ msec. The dead time in this condition is 456 msec as seen in Fig. 6.

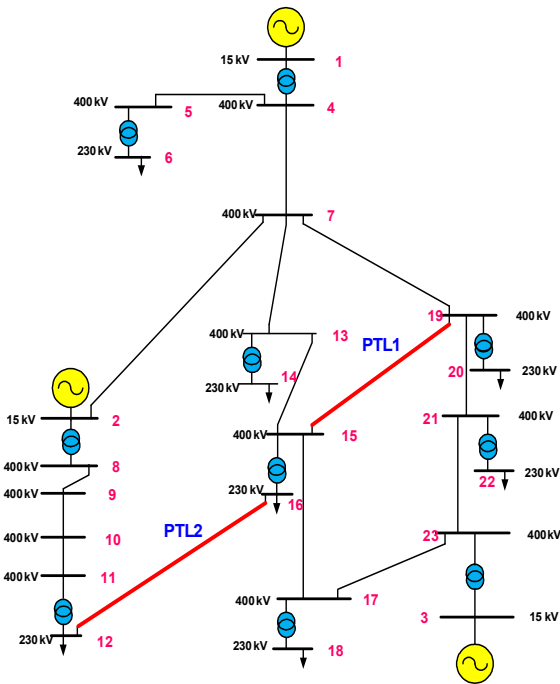


Fig. 4 Under study power network

TABLE I
IMPEDANCE DATA OF THEVENIN EQUIVALENT CIRCUIT AT TWO SIDES OF L1

R_+ [Ω]	X_+ [Ω]	R_0 [Ω]	X_0 [Ω]	Impedance
2.49	35.70	0.35	8.75	External System1
3.1	35.8	1.18	16.3	External System2

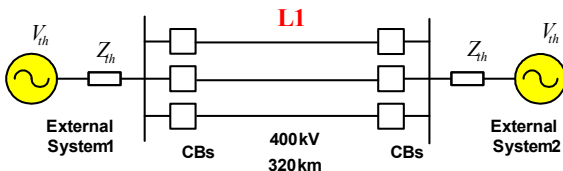


Fig. 5 Under study network (involving L1) using Thevenin equivalent circuit technique

Now, the method of dead time calculation is repeated for L2. Considered model for this line is Jmarti. Also, positive and zero sequence resistance, inductance and capacitance of this PTL have been considered as follows:

$$\begin{aligned}
 R_1 &= 0.012194 \Omega/\text{km} & R_0 &= 0.04297 \Omega/\text{km} \\
 L_1 &= 0.87738 \text{ mH}/\text{km} & L_0 &= 2.5363 \text{ mH}/\text{km} \\
 C_1 &= 0.0129 \mu\text{F}/\text{km} & C_0 &= 0.0046 \mu\text{F}/\text{km}
 \end{aligned}$$

The corresponding impedances of the Thevenin equivalent circuit network at two sides of the PTL as the External system1 and External system2 are shown in Table II.

Also, under study network (involving L2) based on the resulted Thevenin equivalent circuit has been shown in Fig. 7. Then, a transient SLG fault has been assumed in the middle of L2. Voltage waveform at the beginning of faulted phase has been shown in Fig. 8. It is evident from the figure that the SLG fault has been occurred at $t = 190$ msec and the CBs have disconnected faulted phase from the circuit at $t = 200$ msec. The dead time in this condition is 494 msec.

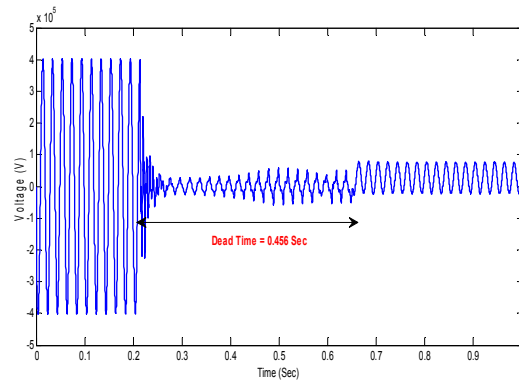


Fig. 6 Voltage waveform at the beginning of faulted phase in L1 for dead time calculation

TABLE II
IMPEDANCE DATA OF THEVENIN EQUIVALENT CIRCUIT AT TWO SIDES OF L2

R_+ [Ω]	X_+ [Ω]	R_0 [Ω]	X_0 [Ω]	Impedance
2.47	33.45	0.27	7.85	External System1
3.1	33.75	1.18	17.13	External System2

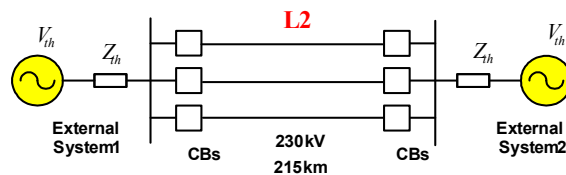


Fig. 7 Under study network (involving L2) using Thevenin equivalent circuit technique

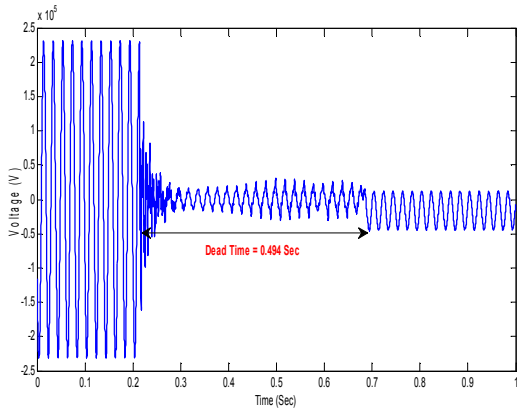


Fig. 8 Voltage waveform at the beginning of faulted phase in L2 for dead time calculation

B. Precise Calculation of Dead Time Using Network Equivalencing in Time Domain

In this section, dead time is calculated for two PTLs L1 and L2 regarding the same situations assumed in the previous section. In fact, the only difference between this section (dead time calculation using network equivalencing in time domain) and the previous section (dead time calculation using Thevenin equivalent circuit) is the external network (remained network except under study line) modeling. The external network modeling in transient study based on the network equivalencing in time domain is very more accurate than the Thevenin equivalent circuit method, so it can be said that calculating of dead time based on the network equivalencing in time domain is more precise and hence more reliable.

Therefore, this method is called “precise” dead time calculation in this paper.

The symbolic extracted network based on the network equivalencing in time domain has been shown in Fig. 9 for each of two PTLs L1 and L2. In this section, studies have been applied for L1 and L2 separately.

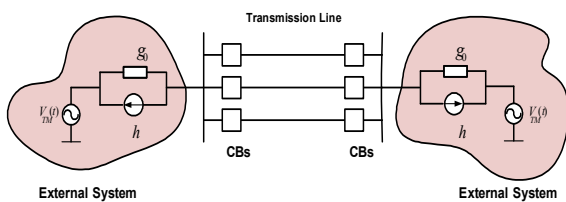


Fig. 9 Under study network (involving L1 or L2) based on the network equivalencing method in time domain

A transient SLG fault is considered in the middle of L1 and for another time in the middle of L2, assuming the similar conditions for this section and the previous section. Voltage waveforms at the beginning of faulted phase for L1 and L2 have been shown in Figs. 10 and 11 respectively. It is evident from these figures that in each of these cases SLG fault has occurred at $t = 190$ msec and the faulted phase has been disconnected from the circuit by CBs at $t = 200$ msec. These

figures show that in this case the dead time is 612 and 257 msec for L1 and L2 respectively.

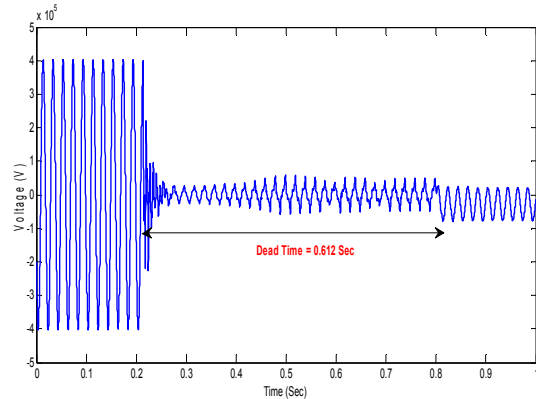


Fig. 10 Voltage waveform at the beginning of the faulted phase in L1 for dead time calculation

V. DISCUSSION

Results of dead time calculation using each of two mentioned approaches have been shown in Table III for L1 and L2. It is evident that the derived dead time based on the proposed approach in this paper (network equivalencing method in time domain) is more in one case (L1) and in the other case (L2) less than the derived dead time by the traditional method (Thevenin equivalent circuit). Reason of this difference is perfectly obvious. Thevenin equivalent circuit approach is very efficiency for deriving model of linear networks consisting of lumped elements. But when elements as PTLs with extensive model exist in network, this method doesn't have adequate accuracy; because, in phenomenons like switching or transient fault, a wide frequency spectrum is established. While Thevenin equivalent circuit is used only at the power frequency, so it has adequate accuracy in this frequency only.

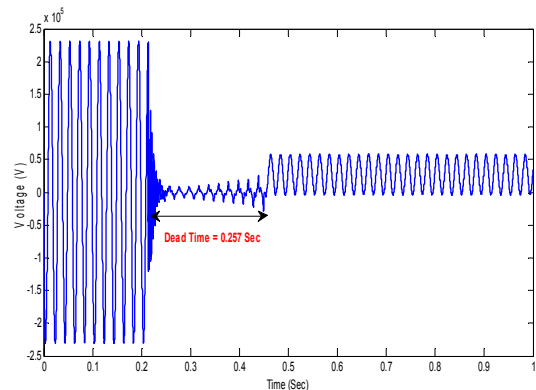


Fig. 11 Voltage waveform at the beginning of the faulted phase in L2 for dead time calculation

TABLE III
RESULTS OF DEAD TIME CALCULATION

Calculated dead time using network equivalent in time domain (millisecond)	Calculated dead time using Thevenin equivalent circuit (millisecond)	Power Transmission Line
612	456	L1
257	494	L2

It is very important that accurate calculation of dead time has an essential part in power system stability. As the SPAR is adjusted based on the calculated dead time, if the considered dead time is less than its real value, the CBs can be closed by the reclosure while the fault is not cleared completely. This can lead to irreparable damages in power system. Moreover if the considered dead time is more than its real value, the CBs may be closed by the reclosure after complete clearing of the fault and this is a serious threat for PTL stability.

Above discussion demonstrates that extreme precision should be applied in high voltage PTLs and the researchers must try to use precise methods (proposed method in this paper) as possible.

VI. CONCLUSION

Precise calculation of dead time has an important part in power network stability. SPAR adjustment based on the inaccurate calculated dead time, is a serious threat for PTLs stability and unsuitable reaction of reclosure can lead to irreparable damages in power system. So extreme precision should be applied in high voltage PTLs and the researchers must try to use precise methods as possible. Using traditional Thevenin or Norton equivalent circuit in network equivalent is not recommended, because when elements as PTLs with extensive model exist in network and phenomena like switching or transient fault is occurred in network, this method doesn't have adequate accuracy. Therefore, a method using equivalent in time domain is proposed in this paper that acts based on the response of external network to a special actuating signal. This method is implementable in EMTP-ATP environment. Precise calculation of dead time in the proposed technique results in accurate adjustment of SPARs and hence increasing the high voltage PTL stability.

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