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A Practical Method for Calculating the Reclosing Time in Long Lines with Reactors

Case Study: Transmission Lines of Yazd Province

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ABSTRACT

In transmission networks, the recloser is used to detect and interrupt transient faults, isolate faults, manage the network structure and increase reliability. This instrument interrupts momentary faults by opening and closing its faulty downstream power system. An auto-reclose method can be used to trip the faulted line and re-energize it after an intentional time delay. This time delay is normally required for the de-energization of the fault arc otherwise the arc will restrike. One of the most important factors that should be considered in reclosing in long lines is the ability to turn off the secondary arc by means of Neutral grounding resistors (NGR) in the reactor neutral location. Due to many factors such as line length change, NGR design, etc., it is very important to determine the proper dead time. This paper presents a auto-reclosing study of 400kV transmission lines. The success of the auto-reclosing depends on the extinction of the secondary arc. In the proposed method, it is explained with some real examples of Yazd transmission network lines that NGR cannot be expected to completely suppress the secondary arc, so the maximum value of the secondary arc current and dead time will be calculated with the reverse calculation method.

1. Introduction

The purpose of a power system is to produce and transmit electrical energy and distribute it among consumers with high reliability and economy. The most important factor threatening the reliability of the system is a short circuit that causes sudden and sometimes severe changes on the power grid [1-3]. A large current that flows when a fault occurs can cause a fire at the fault location and cause mechanical damage throughout the system[4]. Due to the size of the power system, the disturbance caused by a fault is so great that the system becomes inoperable without the fault-resolving equipment [5-7]. To fix the fault, it is not enough to install the switching equipment, but to control the circuit breakers, there must also be protective devices that detect the fault, which are designed according to the specifications and requirements of the power system. Protective relays and relaying systems reveal abnormal conditions such as faults in the system and use automatic switches to disconnect the faulty equipment from the system [8]. If for any reason, the current and voltage are out of the normal state; A fault has occurred that can be permanent or transient[9]. A recloser is a relay that disconnects the line during a fault and connects it automatically after a certain period of time (a fraction of a second) and this work is done for both transient faults and permanent faults in the hope that the type of fault is transient[10-12]. However, for permanent

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faults, this creates dynamic stress and additional heat for the equipment, which is not desirable. As a result, if there is a fault in the transmission lines and there are changes in the line parameters, first the type of fault, and then if it is transient, the recloser will perform the action of closing the arm until the fault is removed, and if the fault is permanent, the recloser relay will prevent the arm from closing[13]. It is necessary to receive information and guidance from the study and protection operational and planning groups of each area to determine the appropriate recloser of that area's information. Below are some important considerations for a transfer level recloser[14]:

- System stability
- System security
- Continuity of service

The most important parameters of an automatic recloser design are:

- Dead Time
- Reclaim Time
- Single or multi-trip

These parameters are influenced by:

- Type of protection
- type of switchgear
- Possible stability problems

In general, the reclosing time should be such that the arc is turned off in the power switch, and the reclosing time should be after the Dead Time[15]. The main purpose of this article is to determine Dead Time in long transmission lines.

2. Reclosing on lines with reactors

Reclosing is one of the best methods used to improve network stability and maintain voltage. In the case of long lines with single-phase trip capability[16]. when one phase is interrupted, the other two phases are energized, and capacitive and self-induction occurs between the disconnected phase and the two energized phases, this induction feeds and remains the fault, in this way, the said induction leads to It is used to create reverse voltage or secondary voltage on the fault path[17-19]. If the growth rate of this voltage is very fast, it leads to the creation of the arc again and keeps the path of the arc warm. This voltage is formed just before reclosing, and the reclosing operation can be successful only when the arc is turned off until reclosing, that is, during the dead time[20]. The time of the secondary arc depends on several factors, the most important of which are the amount of arc current, the secondary voltage, the length of the arc, and even external factors such as wind speed[21]. The best known way to suppress the secondary arc is to put the NGR in the neutral place of the reactor[22]. NGR installation is effective when the line is properly transposed, despite the NGR, the inductor and capacitor of the line and the reactor make the parallel resonance circuit and suppress and eliminate the secondary arc current. Fig.1 shows the three-phase equivalent circuit of a line with reactor and NGR during a single-phase fault [23].

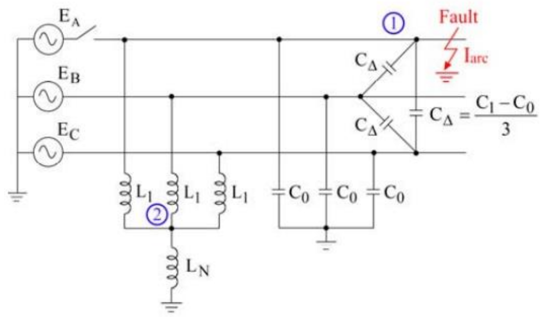

Fig. 1. Three-phase equivalent circuit of a line with reactor and NGR during single-phase fault

Theoretically, when two healthy phases can no longer feed the fault, the self-capacitor circuit forms a parallel resonance with infinite impedance, or:

$$\frac{1}{\omega \cdot 2(C_1 - C_0)/3} = \omega \cdot \frac{L_1^2 + 3L_1L_N}{2L_N} \quad (1)$$

with the following parameter:

C_0: zero sequence capacitance of transmission line.

L_1: inductance of shunt reactor.

L_N: inductance of neutral reactor.

ω: grid angular frequency.

Ea, Eb, Ec: the voltage phasors of sources for phases a, b and c, respectively

The value of L_N or NGR inductance that theoretically completely suppresses the arc can now be obtained from e.g. (2).

$$L_N = \frac{(C_1 - C_0)/3}{\left(\frac{1}{\omega L_1}\right)^2 - \frac{1}{L_1}(C_1 - C_0)} \quad (2)$$

The above topics were discussed from a theoretical point of view, but as discussed below, due to the different design parameters, practical and experimental methods should be used, which will be discussed in the next section.

3. Mathematical model analysis

It is explained with an example that NGR cannot be expected to completely suppress the secondary arc during the fault, to show this, the Yazd 1-Nakhlestan line, which includes the reactor as well as the neutral reactance, is considered. The length of this line is 120 km. The steps to determine the reclozinc time for this line are as follows.

$$S_{\text{reactot}} = 50\text{MVA} \qquad L_{\text{line}} = 120\text{km} \quad (3)$$

$$\omega = 2 \cdot \pi \cdot 50\text{Hz}$$

$$V_{ph\_n} = \frac{400\boldsymbol{kV}}{\sqrt{3}} \quad (4)$$

$$X_r = \frac{3 \cdot V_{\text{ph\_n}}{}^2}{S_{\text{reactot}}} \qquad X_r = (3.2 \cdot 10^3)\Omega \quad (5)$$

$$L_1 = \frac{X_r}{\omega} \qquad L_1 = 10.186\boldsymbol{H} \quad (6)$$

$$C_{1\_\text{line\_per\_kilometer}} = 0.01351642\,\frac{\boldsymbol{\mu F}}{\textbf{km}} \tag{7}$$

$$C_{1\_\text{line}} = C_{1\_\text{line\_per\_kilometer}} \cdot L_{\text{line}} = 1.622\mu$$

$$C_{0\_\text{line\_per\_kilometer}} := 0.00740586\,\frac{\boldsymbol{\mu F}}{\textbf{km}} \tag{8}$$

$$C_{0\_\text{line}} = C_{0\_\text{line\_per\_kilometer}} \cdot L_{\text{line}} = 0.889\mu\boldsymbol{F}$$

$$L_N = \frac{\left(C_{1\_\text{line}} - C_{0\_\text{line}}\right)}{3\cdot\left(\left(\frac{1}{L_1\cdot\omega}\right)^2 - \frac{1}{L_1}\left(C_{1\_\text{line}} - C_{0\_\text{line}}\right)\right)} \tag{9}$$

$$L_N = 9.522\text{H}$$

$$X_N = L_N\cdot\omega \tag{10}$$

$$X_N = (2.992\cdot 10^3)\Omega$$

The actual and installed value of NGR reactance in Yazd 1 is equal to 1366 ohm, while the value theoretically required for complete arc suppression is equal to 2992 ohm. One of the main reasons is that the lower reactance value of NGR requires lower insulation voltage and is much more economical.

In other words, in the current conditions of the Yazd1-Nakhlestan line and most of the rest of the transmission lines in Iran, the secondary arc is not completely turned off, and we must look for a more practical criterion. This criterion, expressed by Sigreh, is simply stated in Fig.2.

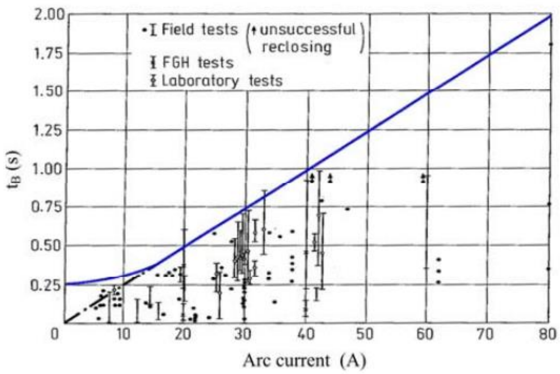

Fig. 2. Arc extinguishing time according to arc current[6]

In Fig.2, the horizontal axis shows the secondary arc current and the vertical axis is the time required for the secondary arc to extinguish. As seen in Fig.2, the arc extinguishing time in terms of arc current is obtained from the following equation.

$$t_B > 0.025 I_{arc} \tag{11}$$

To ensure the deionization of the arc path, 250 msec is added to t_B in the above relationship, and finally, the secondary arc extinguishing time is obtained from the following relationship according to the secondary arc current obtained by multiple tests.

$$t_B \geq 0.25(0.1 I_{arc} + 1) \tag{12}$$

It should be noted that in the above relation, I_{arc} is the maximum current of the secondary arc, which is turned off after t_B. According to the dead time that is set between 0.8sec and 1.2sec. According to e.g.12, the maximum secondary arc current will be between 22A and 38A, and it is obvious that the more pessimistic case, i.e. 1.2sec time, should be considered in the calculations.

Now we have to obtain I_{arc} or secondary arc current by writing two KVL in Fig.2 and assuming that the arc point voltage is zero.

$$\frac{-V_N}{jX_N} + \frac{-E_B}{-jX_{C\Delta}} + \frac{-E_C}{-jX_{C\Delta}} + I_{arc} = 0 \tag{13}$$

$$\frac{V_N}{jX_1} + \frac{V_N - E_B}{-jX_1} + \frac{V_N - E_C}{-jX_1} + \frac{V_N}{jX_N} = 0 \tag{14}$$

In the relations above, V_N is the voltage of the neutral point of the reactor, X_1 is the reactance of the head-of-line reactor in ohms, X_N is the reactance of NGR in ohms, and $X_{C\Delta}$ is the interphase capacitive impedance.

I_{arc} can now be obtained from substituting the above relations as follows.

$$I_{arc} = \frac{E_B + E_C}{\left(3 + \frac{X_1}{X_N}\right)\cdot j\cdot X_1} - \frac{E_B}{j\cdot X_{C\Delta}} - \frac{E_C}{j\cdot X_{C\Delta}} \tag{15}$$

According to the mentioned contents, the secondary arc current for lines with reactors in the Yazd power grid will be obtained as follows.

3.1. *Calculation of secondary arc flow, Yazd1-Nakhlestan line*

According to the relationships stated in the previous part, the secondary arc flow of the Yazd1-Nakhlestan line is calculated in the form of the following relationships.

$$S_{\text{reactot}} = 50\text{MVA} \qquad L_{\text{line}} = 120\text{km} \tag{16}$$

$$\omega = 2\cdot\pi\cdot 50\text{Hz}$$

$$V_{ph\_n} = \frac{400\boldsymbol{kV}}{\sqrt{3}} \tag{17}$$

$$E_B = \frac{400\boldsymbol{kV}\angle -\mathbf{120}\ \boldsymbol{deg}}{\sqrt{3}} \tag{18}$$

$$E_C = \frac{400\boldsymbol{kV}\angle\mathbf{120}\ \boldsymbol{deg}}{\sqrt{3}} \tag{19}$$

$$X_1 = \frac{3\cdot V_{\text{ph\_n}}{}^2}{S_{\text{reactot}}} \qquad X_1 = (3.2\cdot 10^3)\Omega \tag{20}$$

$$X_N = 1366\Omega$$

$$C_{1\_\text{line\_per\_kilometer}} = 0.01351642\,\frac{\boldsymbol{\mu F}}{\textbf{km}} \tag{21}$$

$$C_{1\_\text{line}} = C_{1\_\text{line\_per\_kilometer}} \cdot L_{\text{line}} = 1.622\mu\boldsymbol{F}$$

$$C_{0\_\text{line\_per\_kilometer}} = 0.00740586\,\frac{\boldsymbol{\mu F}}{\textbf{km}} \tag{22}$$

$$C_{0\_\text{line}} = C_{0\_\text{line\_per\_kilometer}} \cdot L_{\text{line}} = 0.889\mu\boldsymbol{F}$$

$$C_\Delta = \frac{C_{1-\text{line}} - C_{0\_\text{line}}}{3} \tag{23}$$

$$X_{C\Delta} = \frac{1}{\omega\cdot C_\Delta} \qquad X_{C\Delta} = (1.302\cdot 10^4)\Omega$$

$$I_{arc} = \frac{E_B + E_C}{\left(3 + \frac{X_1}{X_N}\right)\cdot j\cdot X_1} - \frac{E_B}{j\cdot X_{C\Delta}} - \frac{E_C}{j\cdot X_{C\Delta}} \tag{24}$$

$I_{arc} = -4.225i\boldsymbol{A}$

As it can be seen, the calculated secondary arc current for Yazd1-Nakhestan line is equal to 4.5A and less than the minimum standard current for dead time equal to 1.2sec, so the recloser of Yazd1-Nakhestan line can be activated according to the protection criteria.

In order to show the correctness of the calculations, the simulation of the mentioned line was done in MATLAB environment and the arc current is shown in Fig.3, which is consistent with the results.

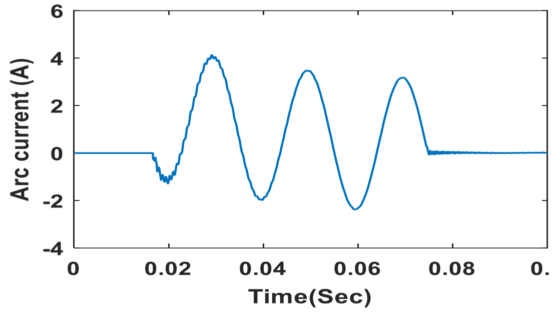

Fig. 3. The fault current (I_arc) is measured in amperes for Yazd1-Nakhestan line

3.2. Calculation of secondary arc current, Yazd1-Sirjan line

Another long line considered in this article is Yazd1-Sirjan long line with a length of 295 km.

$$S_{reactot} = 50\text{MVA} \qquad L_{line} = 295\text{km} \quad (25)$$
$$\omega = 2 \cdot \pi \cdot 50\text{Hz}$$
$$V_{ph\_n} = \frac{400\boldsymbol{kV}}{\sqrt{3}} \quad (26)$$
$$E_B = \frac{400\boldsymbol{kV}\measuredangle - \boldsymbol{120\ deg}}{\sqrt{3}} \quad (27)$$
$$E_C = \frac{400\boldsymbol{kV}\measuredangle\boldsymbol{120\ deg}}{\sqrt{3}} \quad (28)$$
$$X_1 = \frac{3 \cdot V_{ph\_n}{}^2}{S_{reactot}} \qquad X_1 = (3.2 \cdot 10^3)\Omega \quad (29)$$
$$X_N = 1275\Omega$$
$$C_{1\_line\_per\_kilometer} = 0.01351642\frac{\boldsymbol{\mu F}}{\textbf{km}} \quad (30)$$
$$C_{1\_line} = C_{1\_line\_per\_kilometer} \cdot L_{line} = 3.912\boldsymbol{\mu F}$$
$$C_{0\_line\_per\_kilometer} = 0.00808051\frac{\boldsymbol{\mu F}}{\textbf{km}} \quad (31)$$
$$C_{0\_line} = C_{0\_line\_per\_kilometer} \cdot L_{line} = 2.384\boldsymbol{\mu F}$$
$$C_\Delta = \frac{C_{1-line} - C_{0\_line}}{3} \quad (32)$$
$$X_{C\Delta} = \frac{1}{\omega \cdot C_\Delta} \qquad X_{C\Delta} = (6.247 \cdot 10^3)\Omega$$
$$I_{arc} = \frac{E_B + E_C}{\left(3 + \frac{X_1}{X_N}\right) \cdot j \cdot X_1} - \frac{E_B}{j \cdot X_{C\Delta}} - \frac{E_C}{j \cdot X_{C\Delta}} \quad (33)$$
$$I_{arc} = -23.868i\boldsymbol{A}$$

As explained, the dead time is equal to 0.8sec, the maximum amount of secondary arc current that can be turned off is 22A, while the secondary arc current is equal to 23.8A in the existing conditions for Yazd1-Sirjan line, so if the Yazd1-line recloser is activated Sirjan, the value of Dead time must be greater than 0.8sec and preferably equal to 1.2sec.

3.3. Calculation of secondary arc flow, Yazd 2-Sepahan line

$$S_{reactot} = 50\text{MVA} \qquad L_{line} = 250\text{km} \quad (34)$$
$$\omega = 2 \cdot \pi \cdot 50\text{Hz}$$
$$V_{ph\_n} = \frac{400\text{kV}}{\sqrt{3}} \quad (35)$$
$$E_B = \frac{400\text{kV}\measuredangle - 120\text{ deg}}{\sqrt{3}} \quad (36)$$
$$E_C = \frac{400\text{kV}\measuredangle 120\text{ deg}}{\sqrt{3}} \quad (37)$$
$$X_1 = \frac{3 \cdot V_{ph\_n}{}^2}{S_{reactot}} \qquad X_1 = (3.2 \cdot 10^3)\Omega \quad (38)$$
$$X_N = 1277\Omega$$
$$C_{1\_line\_per\_kilometer} = 0.01326207\frac{\mu\text{F}}{\text{km}} \quad (39)$$
$$C_{1\_line} = C_{1\_line\_per\_kilometer} \cdot L_{line} = 3.316\mu\text{F}$$
$$C_{0\_line\_per\_kilometer} = 0.00808051\frac{\mu\text{F}}{\text{km}} \quad (40)$$
$$C_{0\_line} = C_{0\_line\_per\_kilometer} \cdot L_{line} = 2.02\mu\text{F}$$
$$C_\Delta = \frac{C_{1-line} - C_{0\_line}}{3} \quad (41)$$
$$X_{C\Delta} = \frac{1}{\omega \cdot C_\Delta} \qquad X_{C\Delta} = (7.372 \cdot 10^3)\Omega$$
$$I_{arc} = \frac{E_B + E_C}{\left(3 + \frac{X_1}{X_N}\right) \cdot j \cdot X_1} - \frac{E_B}{j \cdot X_{C\Delta}} - \frac{E_C}{j \cdot X_{C\Delta}} \quad (42)$$
$$I_{arc} = -18.22i\text{A}$$

Dead time for recloser line Yazd 2 - Sepahan should be equal to 1.2 sec.

3.4. Calculation of secondary arc current, Yazd 2-Sarv line

$$S_{reactot} = 50\text{MVA} \qquad L_{line} = 125\text{km} \quad (43)$$
$$\omega = 2 \cdot \pi \cdot 50\text{Hz}$$
$$V_{ph\_n} = \frac{400\text{kV}}{\sqrt{3}} \quad (44)$$
$$E_B = \frac{400\text{kV}\measuredangle - 120\text{ deg}}{\sqrt{3}} \quad (45)$$
$$E_C = \frac{400\text{kV}\measuredangle 120\text{ deg}}{\sqrt{3}} \quad (46)$$
$$X_1 = \frac{3 \cdot V_{ph\_n}{}^2}{S_{reactot}} \qquad X_1 = (3.2 \cdot 10^3)\Omega \quad (47)$$
$$X_N = 986\Omega$$
$$C_{1\_line\_per\_kilometer} = 0.01264437\frac{\mu\text{F}}{\text{km}} \quad (48)$$
$$C_{1\_line} = C_{1\_line\_per\_kilometer} \cdot L_{line} = 1.581\mu\text{F}$$
$$C_{0\_line\_per\_kilometer} = 0.00784695\frac{\mu\text{F}}{\text{km}} \quad (49)$$
$$C_{0\_line} = C_{0\_line\_per\_kilometer} \cdot L_{line} = 0981\mu\text{F}$$
$$C_\Delta = \frac{C_{1-line} - C_{0\_line}}{3} \quad (50)$$
$$X_{C\Delta} = \frac{1}{\omega \cdot C_\Delta} \qquad X_{C\Delta} = (1.592 \cdot 10^4)\Omega$$

$$I_{arc} = \frac{E_B + E_C}{\left(3 + \frac{X_1}{X_N}\right) \cdot j \cdot X_1} - \frac{E_B}{j \cdot X_{C\Delta}} - \frac{E_C}{j \cdot X_{C\Delta}} \quad (51)$$

$$I_{arc} = -2947iA$$

Due to the insignificant secondary arc current in Yazd2-Sarv line, the reclosing dead time of this line can be reduced to 0.8 sec.

3.5. Calculation of secondary arc flow, Nakhlestan - Golshan line

$$S_{reactot} = 50MVA \qquad L_{line} = 280km \quad (52)$$

$$\omega = 2 \cdot \pi \cdot 50Hz$$

$$V_{ph\_n} = \frac{400kV}{\sqrt{3}} \quad (53)$$

$$E_B = \frac{400kV\measuredangle - 120 \text{ deg}}{\sqrt{3}} \quad (54)$$

$$E_C = \frac{400kV\measuredangle 120 \text{ deg}}{\sqrt{3}} \quad (55)$$

$$X_1 = \frac{3 \cdot V_{ph\_n}{}^2}{S_{reactot}} \qquad X_1 = (3.2 \cdot 10^3)\Omega \quad (56)$$

$$X_N = 1318\Omega$$

$$C_{1\_line\_\_per\_kilometer} = 0.01351642\frac{\mu F}{km} \quad (57)$$

$$C_{1\_line} := C_{1\_line\_per\_kilometer} \cdot L_{line} = 3.785\mu F$$

$$C_{0\_line\_\_per\_kilometer} = 0.00740586\frac{\mu F}{km} \quad (58)$$

$$C_{0\_line} = C_{0\_line\_per\_kilometer} \cdot L_{line} = 2.074\mu F$$

$$C_\Delta = \frac{C_{1-line} - C_{0\_line}}{3} \quad (59)$$

$$X_{C\Delta} = \frac{1}{\omega \cdot C_\Delta} \qquad X_{C\Delta} = (5.581 \cdot 10^3)\Omega$$

$$I_{arc} = \frac{E_B + E_C}{\left(3 + \frac{X_1}{X_N}\right) \cdot j \cdot X_1} - \frac{E_B}{j \cdot X_{C\Delta}} - \frac{E_C}{j \cdot X_{C\Delta}} \quad (60)$$

$$I_{arc} = -28.082iA$$

As can be seen, the secondary arc current is equal to 28A, which according to the discussed criteria, the dead time should be equal to 1.2 sec.

4. Conclusion

In this paper, a novel adaptive single-phase reclosing method for high voltage transmission lines with shunt reactors is proposed. By extracting the amount of fault current in the presence of NGR, how to set the dead time to reclose long lines with head of line reactors was discussed. The investigated lines are long lines of the 400 kV transmission network with different lengths. In this paper, the advantage of the practical and laboratory method over the theoretical method to determine the dead time was investigated and the proper adjustment of the recloser time was calculated by giving real examples. Moreover, this method is easy to implement without large computation and to immune to long-term disturbances including voltage unbalance as well as harmonics. Simulation results and field data are obtained to confirm the performance of proposed method.

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