



Distance protection zone 3 misoperation during system wide cascading events: The problem and a survey of solutions



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ABSTRACT

Distance relay zone 3 misoperation has been responsible for major blackouts around the world. Zone 3 misoperation generally occurs under system wide cascading events such as the 2003 Northeastern US–Canada blackout or under stressed system conditions such as the 2015 Turkish blackout. This paper explains the problem of zone 3 distance protection misoperation. The paper then proceeds to survey the literature for possible solutions to increase distance relay security to prevent distance protection misoperation. Three categories of solutions were proposed in literature to address the problem of zone 3 distance protection misoperation. The first one is anticipation and prevention of misoperation in the planning stage. The second one is communication assisted protection schemes that use remote measurements to enhance relay security. The last one uses local data to enhance distance relay security.

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1. Introduction

With the deregulated market structure in the United States and Europe, grid operators are under more pressure to reap more profits of existing infrastructure due to increased competition. The grid is thus increasingly operated near the threshold of stability. Failure of the grid, better known as blackouts, carries catastrophic economic and societal sequences. Large blackouts tend to be due to either extreme natural events such as hurricanes or a series of events called cascading failures [1]. In this paper, we only focus on cascading events. Those events can be any of the following: line tripping, overloading of other lines, malfunctions of protection systems, power oscillations and voltage instability [2]. The reason that is considered in this paper is distance protection misoperation which is a contributing factor in seventy percent of all cascading events [3]. If not discovered and mitigated in an early stage, cascading events generally lead to a complete blackout. With today's society much dependence on electricity as a form of energy, preventing such damage is of high importance.

Cascading failures are defined as “a sequence of dependent failures of individual components that successively weaken the power system” [4]. Since the 2003 US–Canada blackout, cascading events

have drawn much attention in the industrial and academic community. Even though the world has witnessed many blackouts prior to the 2003 blackout [1], the dramatic causes and consequences of the 2003 blackout have left industrial and academic community with the burden of exploring this phenomenon in more detail. To understand the severity of the 2003 blackout [5], it sufficient to say it had caused the loss of 62 GW which caused the lights to turn off for more than 51 million people in the eastern interconnection. Considering the many components and the bits and pieces involved, a domino effect of events evolved slowly (hours) or fast (seconds) according to the region causing a degradation of the integrity of the system leading ultimately to a complete blackout. The main reason of the 2003 blackout was distance relay misoperation. Daunting efforts had to be exerted to gain more knowledge and understanding of the underlying phenomenon.

Relays by design act quickly to remove the fault from the system by disconnecting faulted lines. However, sometimes relays fail to perform such function which is considered a protection system misoperation. Of all protection system misoperations that lead to cascading events, this paper focuses exclusively on distance protection misoperation. A protection system misoperation is defined as “a failure to operate as intended for protection purposes” [6]. Various categories are given for misoperation in [6]. However, in this paper the word misoperation will be used exclusively to mean only one of them, namely, an operation in which a protection system trips a healthy line due to heavy loading when no fault exists. In other words, other causes of distance protection misoperation

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such as power swing are not considered in this paper. Notable cascading events [2,7] begin with lines that were tripped due to actual faults. The tripping of those faulty line causes the current flowing in those lines to be redistributed to adjacent lines. Those lines may be overloaded and thus tripped incorrectly – protection misoperation – which may trigger a sequence of cascading events that might ultimately lead to a blackout. It should be noted that regardless of the initial triggering events – whether a fault or not – that cause cascading events, historically those cascading events were triggered under stressful system conditions [5,8].

As mentioned in [2], one of the effective ways to prevent cascading events is to specify potential undesirable relay operations ahead of time. In this paper, we show that even though distance protection misoperation can be anticipated ahead of time, prevention of this misoperation is not possible with distance protection principle only because the distance protection principle is not able to be selective in some regions of its operation.

The paper is organized as follows: Section 2 provides a sample distance relay that is set according to NERC standards. Once this relay is set according to NERC directives, it will be explained in the same section that the relay may still misoperate under various operating conditions. Anticipation and detection of distance relay misoperation in the planning stage is described Section 3. Section 4 provides an overview of the communication assisted schemes that have been proposed to eliminate the distance protection misoperation. Lastly, Section 5 offers a survey on the methods that were suggested in literature to enhance the distance protection security using local data only.

2. The distance protection misoperation problem

On August 14th of 2003 [5], the US eastern interconnection suffered one of the largest blackouts in the recent US history. Three 345 kV transmission lines sagged into untrimmed trees during the hot summer days. The tripping of those lines caused another 345 kV transmission line to carry substantial system load. The heavy loading of this last line coupled with relatively low system voltage, caused the distance relay to confuse a heavy loading situation for uncleared zone 3 fault as the impedance entered the third zone of protection which in turn resulted in tripping of the heavily loaded line. The tripping of the healthy yet heavily loaded line worsened system conditions leading to a chain of events that ultimately led to system collapse. Also, on March 31st of 2015 [9], the Turkish grid suffered the worst blackout ever recorded since 1999 when an earthquake caused a complete shutdown of the grid. On the contrary to the 1999 earthquake, the 2015 blackout was caused by a impedance protection misoperation that tripped a heavily loaded line on the 400 kV transmission level even though there was no fault on the tripped line or anywhere in the transmission network. As can be seen from the examples in [5,9] in which distance protection misoperation have been the main cause of the blackouts or in [10] in which distance protection misoperation have been studied in the IEEE 118 bus system, a distance protection misoperation is characterized by a distance protection system seeing a heavy load on a line as a fault. This confusion arises from the fact that the impedance measured by the impedance protection system coincides with that of a fault. The reason for the heavy load can be due to load shifting after a fault as in the 2003 US–Canada blackout [5] or due to lines out of service for maintenance causing one line to carry substantial system power transfer as in the 2015 Turkish blackout [9] or due to any unforeseen reasons.

To illustrate that this confusion is not tied up with certain system conditions but rather inherent insecurity in the distance protection principle, the single line diagram shown in Fig. 1 is used to formulate the problem in general terms. It will be shown below that

this insecurity always exists and the degraded system conditions only excite it; that is, for some regions in the impedance protection zone the protection system is not able to be selective between a fault and non-fault condition. Without the degraded system conditions, it is highly unlikely that a distance protection misoperates. Even though, degraded system conditions can be anticipated in the planning stage, the system operator will have nothing in hand to prevent a distance protection misoperation if local function of the distance protection is used alone. It is important to keep in mind that distance protection systems are set locally with the help of the impedance of adjacent lines without any information about the system load until the coordination study phase. In the coordination study phase, the transmission line owner checks all settings against applicable standards. This is explained in detail in [11]. In the following paragraphs, we will set up the relay settings first then discuss what happens in system wide cascading events.

In Fig. 1, the distance protection relay that will be studied is the relay at point A of line A–C. Line A–C is connected to three (3) lines, namely C–M, C–N and C–P. The number of lines connected to line A–C will not affect zone 1 or zone 2 settings but will affect zone 3 settings. As will be seen below, tripping in zone 3 becomes more insecure with more lines connected to line A–C as zone 3 reach becomes larger. To simplify the analysis, all lines are assumed to have the same impedance as well as the short circuit level. However, as will be explained below, this simplification does not affect the generality of the problem formulation. The impedance and the rating of the lines are 60Ω and 3000 Amp, respectively and are taken from [12]. The setting of zone 1 is assumed to be 0.85 of the line impedance. Zone 2 setting is assumed to be 1.2 of the line impedance. However, some consideration is needed to set the third zone. The third zone has to be set such that it can protect the longest adjacent line (assumed to be line C–P in this case) and to protect 20% beyond that line to provide backup to the remote circuit breakers. In case of a bolted three phase fault on line C–P and assuming that the short circuit contributions of all buses is given in Fig. 1 by I_{index} where *index* is the bus name (being M, N, A or P), the voltage at distance protection system at A can be written as given in Eq. (1).

$$V_A = I_A \times Z_A + Z_P \times (I_M + I_A + I_N) \quad (1)$$

The impedance that is seen by the relay A can then be written as in (2)

$$Z_R = \frac{V_A}{I_A} = Z_A + Z_P \left(1 + \frac{I_M + I_N}{I_A} \right) \quad (2)$$

Eq. (2) will only be applicable to faults on line C–P, if we need to include 20% for the line that is beyond bus P, then the impedance Z_P in (2) has been replaced by $1.2 \times Z_P$. Using the data in [12] and assuming all lines are identical as well as their short circuit contribution, then the setting of zone 3 will be $Z_A + 3.6 \times Z_P = 4.6 \times Z_A$. The three zones are plotted in Fig. 2.

After setting up the relay locally, applicable standards and directives need to be applied to the settings for compliance purposes. This step involves running worst case power flow in the summer peak case. The most notable directive is the load encroachment. The load encroachment zone is an area of the protection zone in which the load impedance “encroaches” – intrudes – upon the fault impedance. Load encroachment will obviously cause misoperation and should be removed from the zone of protection [12]. To plot the load encroachment zone according to NERC directives [6,12,13], the load zone should include the point which corresponds to 150% line loading and 0.85 per unit voltage. Thus the load encroachment locus of the distance relay at A will consist of two parts. The first part will be an arc of circle of radius given in Eq. (3) which is given as arc **RIT** in Fig. 1. This arc **RIT** corresponds to the least impedance that the relay should not issue a trip command for. The other characteristic load lines will be two lines making an angle of $\pm 30^\circ$ with the

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