Electrical Power and Energy Systems 62 (2014) 391–397

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Stability enhancement of multi-machine systems using adaptive reclosing of transmission lines

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ARTICLE INFO

Article history:
Received 22 April 2013
Received in revised form 3 April 2014
Accepted 5 April 2014
Available online 2 June 2014

Keywords:
Transmission lines
Adaptive reclosing
Transient stability
SIME
Power swing mitigation

ABSTRACT

When a fault occurs in high voltage (HV) and Extra High Voltage (EHV) lines, they could automatically be re-entered to the circuit by auto-reclosing operation of transmission switches after passing a certain time from the first tripping operation. It is due to the fact that most of the faults occurred in HV/EHV transmission systems have a corresponding arc which could be removed just after de-energizing the line. To ensure successful reclosing, de-energizing interval addressed as dead time is conventionally determined, based on the calculation of the time needed for quenching subsequent weakened secondary arc. However, on-fault reclosing is probable even if dead time is conservatively selected. It can lead to severe power swings and put the system in danger of instability especially in vastly loaded networks. These swings will be intensified or weakened upon rotor angular speeds of dominant generators in reclosing instant, which is the key factor in acceleration or deceleration of power swing. Therefore power oscillation can be mitigated by adaptive selection of dead time. In this paper, a new method for dead time calculation is proposed in order to mitigate power oscillations effectively. The proposed method can also be implemented in on-line monitoring and control algorithms due to low amount of calculation. In this approach, single machine infinite bus equivalent (SIME) method is used for the evaluation of power oscillations.

Introduction

Clearance instance of the fault is usually followed by electrical power swings across a multi-machine network. These swings are likely to be hazardous as they potentially mislead distance protection and have thermal effects on generators. When a large amount of electrical power is oscillating, aforementioned effects could result in cascading outages of transmission lines, out of step condition for network machines and eventually transient instability. Therefore, prevention from dangerous power swings is essential, especially in new deregulated networks which involve highly loaded lines. Reclosing the faulty phase in transmission lines is one of the methods for power swing mitigation and consequently improving the system stability. The faulty line is likely to be restored since most of the faults occurred in HV and EHV transmission system are transient events and cleared only by line de-energizing. After de-energizing the line, a weakened arc called "secondary arc" still exists in fault location due to the electrostatic and electromagnetic coupling of faulty phase with other phases.

Conventionally, reclosing is delayed based on the time required for secondary arc to be quenched, which in turn depends on voltage level, line configuration and weather condition. This intentional delay in reclosing called dead time is practically defined as a fixed value. It implicates that reclosing logic has been launched just after passing a pre-determined time from first tripping. However, its a controversial issue since fault nature, whether permanent or transient is not known at reclosing moment. Moreover, secondary arc quenching instant highly depends on weather conditions which leads to uncertainties in the dead-time calculation. Therefore, an on-fault reclosing is always probable due to this blind operation which endangers the network stability, especially in highly loaded networks. In order to reclose smartly, some approaches have been suggested recently [1,2] which address the term "adaptive reclosing schemes".

Utilizing faulty phase voltage dominantly, fault nature and arc extinction time are determined according to secondary arc characteristics, post-extinction features or a mixed approach [3]. On the other hand, even using these innovative methods, wrong detection is not absolutely unlikely [4]. As a result, on-fault reclosing must be studied even when a reclosing scheme is adaptively designed.

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http://dx.doi.org/10.1016/j.ijepes.2014.04.013

However, post-reclosing stability is influenced by dead time value according to fault nature (permanent or transient). The least oscillating power could be observed if the dead time is properly selected. On the contrary, subsequent dangerous power swings and even transient instability may be resulted in the case of poor dead time selection. In this way, its not appropriate to reclose as fast as possible because fastest reclosing on permanent fault is similar to impose the system to a more durable fault, endangering transient stability.

Time-domain simulation is the simplest way for scrutinizing the impact of the dead time selection on transient stability of the system. However, this method cannot be utilized in real-time evaluation of the electrical network due to the large number of contingencies that shall be studied, taking considerable time.

To reduce overall calculation time in transient stability evaluation, several methods have been proposed so far [5]. One of these methods is single machine equivalent (SIME) which has practically been utilized. SIME is a new form of Extended Equal Area Criterion method [6] and used for analyzing of rotor angle oscillations [7] and therefore able to evaluate post-reclosing transient state.

This paper proposes a new method for optimum dead time selection. The goal is mitigation of power oscillations and network transient stability enhancement in post-reclosing state, using SIME as oscillation evaluator. The paper is organized in four sections. In section 'Background' relevant approaches proposed so far and also, SIME method are briefly reviewed. The proposed method is represented in section 'Proposed method'. Finally, in section 'Simulations', method eligibility will comparatively be demonstrated using several simulations.

Background

In case of permanent and transient faults occurred in power systems, transmission lines could be recovered after exposing to fault condition by auto-reclosing operation of transmission switches automatically considering a short time needed for reclosing. It is due to the fact that most of the faults occurred in HV/EHV transmission systems have a corresponding arc which could be removed just after de-energizing the line. To ensure successful reclosing, de-energizing interval called dead time is conventionally determined, based on the calculation of the time needed for quenching subsequent weakened secondary arc. However, on-fault reclosing is probable even if dead time is conservatively selected. It can lead to possible severe power swings and put the system in danger of instability especially in vastly loaded networks. These swings will be intensified or weakened up to rotor angular speeds of dominant generators in reclosing instant, which is the key factor in acceleration or deceleration of power swing. Therefore power oscillation can be mitigated by optimal selection of dead time.

Optimal reclosing

After the fault occurrence and line de-energizing, best reclosing time can be evaluated depends on "fault persistence". Indeed, the system trajectory after reclosing is likely to be more crucial, in the case of fault presence in reclosing instant, compared to state that the fault is cleared during dead time. According to above clarification, the study is divided into two separate parts:

a. The fault is assumed to be present on the line (permanent fault).
b. After passing dead time, the fault is cleared and no longer exists on the line (transient fault).

In order to select a best reclosing time, one study suggests using the total kinetic energy of all machines [8,9]. However, some wrong assessments can be observed via this method [10]. In contrast, more acceptable results are obtained by calculation of transient energy function (TEF) for the entire network [11]. Unfortunately, this method cannot be utilized, due to formidable construction of TEF, relevant large amount of calculation and difficulties in modeling of some network elements in the function. These reasons cause the method to be far from practical implementation. Closer to reality, a method based on switching time optimization is proposed by [10]. Results obtained by this method are appropriate, despite of large amounts of complex calculations which makes it hardly applicable in online schemes. Investigation conducted in this paper, utilizes findings introduced in [12] which studies optimal reclosing for One Machine to Infinite Bus (OMIB) network, similar to TEF minimization reviewed earlier. The oscillation reduction issue is investigated using rotor angle trajectory. The following criteria are obtained depends on fault persistence:

a. *Permanent fault:* In this case, to moderate oscillation, reclosing must be done when OMIB machine speed is at its low point. In other words, the following equation must be satisfied:

$$\delta = \delta_s,\ \dot{\delta} < 0 \tag{1}$$

In this equation, δ is instantaneous rotor angle value and δ_s Represents stable value of rotor angle, after the fault occurrence and line de-energizing.

b. *Transient fault:* If the fault is cleared at reclosing instant and the machine is considered as generator for all trajectory points, then reclosing at the low point of instantaneous rotor angle will be the optimum case from the oscillation reduction perspective. The criterion can mathematically be expressed as:

$$\dot{\delta} = 0,\ \ddot{\delta} > 0 \tag{2}$$

SIME method

SIME is a powerful assessment method for network transient stability evaluation. SIME method is based on network machine classification for critical and non-critical groups. Utilizing these two groups, an equivalent One Machine to Infinite Bus circuit will be extracted. To identify critical group machines (CMs), SIME starts exploring the output data of time-domain simulation as soon as the system enters its post fault phase, considering a few candidate decomposition patterns. The parameters of these candidates δ, ω, M, P_m, P_e (these parameters represent angle, speed, inertia coefficient, mechanical power and electrical power respectively) are computed from corresponding individual machine parameters [13]. The candidate OMIB which firstly reaches below conditions is declared as critical OMIB and this process is then halted for the current step:

$$P_a = 0,\ \dot{P}_a > 0 \tag{3}$$

In the above expression, P_a is the acceleration power which is defined as:

$$P_a = P_m - P_e \tag{4}$$

Detailed formulation can be found in [6]. Indeed the most important benefit of SIME method is early detection of instable contingencies, according to above context. However SIME is capable of assessing and ranking of stable scenarios, despite challenges existing in CMs detection. In addition, generation rescheduling in optimal power flow study can be accomplished using SIME