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A multi-agent approach for enhancing transient stability of smart grids

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ABSTRACT

Transient stability, an important issue to avoid the loss of synchronous operation in power systems, can be achieved through proper coordination and operation of protective devices within the critical clearing time (CCT). In view of this, the development of an intelligent decision support system is useful for providing better protection relay coordination. This paper presents an intelligent distributed agent-based scheme to enhance the transient stability of smart grids in light of CCT where a multi-agent framework (MAF) is developed and the agents are represented in such a way that they are equipped with protection relays (PRs). In addition to this, an algorithm is developed which assists the agents to make autonomous decision for controlling circuit breakers (CBs) independently. The proposed agents are responsible for the coordination of protection devices which is done through the precise detection and isolation of faults within the CCT. The agents also perform the duty of reclosing CBs after the clearance of faults. The performance of the proposed approach is demonstrated on a standard IEEE 39-bus test system by considering short-circuit faults at different locations under various load conditions. To further validate the suitability of the proposed scheme a benchmark 16-machine 68-bus power system is also considered. Simulation results show that MAF exhibits full flexibility to adapt the changes in system configurations and increase the stability margin for both test systems.

Introduction

Power systems are large-scale highly nonlinear systems and equipped with large synchronous generators which supply electric power into the load centers [1]. Since the behaviors of power systems are continuously changing, the centralized operation and control of such large-scale system is an extremely challenging task [2]. To alleviate these challenges, the use of advanced networking as well as information and communication technologies (ICTs) have motivated in recent years to operate and control the conventional power grid in a smarter way which is known as a peer-to-peer or distributed multi-agent system (MAS) [3]. For smarter operation of conventional power grids, the grids needs to be interconnected in a distributed and interactive manner for the well suitability of distributed multi-agent technologies. Smart grids are interconnection of among different nodes along with smart meters, sensors and actuators like phasor measurement units (PMUs) superimposed on the physical grid components. Though the concept of smart grids adds new dimensions to the operation of conventional power systems, there are more complexities due to the addition of more smart devices. However, the implementation of multi-agent frameworks (MAFs) significantly reduces the complexities in smart grid protection and securities due their distributed characteristics, dynamic adaptability, and flexibility [4]. A typical node of physical smart grid architecture is shown in Fig. 1, where each node represents a generator with necessary control equipments, a protective relay and an electrical load connected to the utility grid through a transmission line.

Electric power systems are vulnerable to several disturbances such as faults or sudden changes in loads which cause transient instability and consequently, widespread blackout. Recent blackouts in different countries have illustrated the importance and vital need for the further investigations into the transient stability [5]. Transient stability is normally characterized as an ability to remain in synchronism when subject to large disturbances [6]. The transient stability problem is concerned with the stability of power systems and hence, the process of fault detection, isolation and reclosing is indispensable [7]. The critical clearing time (CCT), a maximum time by which a fault must be cleared to preserve system stability, is a vital factor for faster transient stability assessment [8]. During a three-phase short-circuit fault, the online generators may lose their synchronism and consequently, the system may collapse without proper relay coordination. Therefore,

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proper relay coordination is highly desirable to clear the fault before the CCT as this returns a system to stable operating point. Since the CCT plays a vital role for enhancing the transient stability of power systems, the intelligent decision making approaches are useful to enhance the transient stability in a smarter way.

Some intelligent meta-heuristic techniques like genetic algorithm (GA), particle swarm optimization (PSO), simulated annealing (SA), and tabu search (TS) have been extensively used for research in power system protection [9]. However, a key disadvantage of these approaches is the centralized operation which handles a huge amount of data with high communication capability. Over the past few decades, MAFs have been widely used in power engineering research to solve several challenging issues and some examples are power system restoration and reconfiguration, fault analysis and diagnosis, secondary voltage control, wide area control, optimal reactive power dispatch, energy resource scheduling, and protection [10–18]. Though the transient stability assessment is an established research area in power systems, there exist a few applications of agent-based concepts to solve this problem.

A network of real-time closed-loop wide-area decentralized power system stabilizers (WDPSSs) has been proposed in [19] for transient stability enhancement which is based on the reinforcement learning (RL) method and MAS. In [19], real-time wide-area measurement data has been processed and utilized to design a set of stability agents through the RL method and MAS. An agent-based fast valving scheme of turbines has been presented in [20] to improve the transient stability where a tracking agent tracks the generators rotor angle to determine power system instability and a control agent initiates the control action according to the output of the tracking agent. In practice, the rotor angle of generators cannot be measured conveniently [2,21]. A robotic ball-catching algorithm along with MAF is proposed in [22] for online transient stability analysis with post-fault valve control application where the algorithm is used for predicting the instability for out of synchronizing machines. Another multi-agent approach has been proposed in [23,24] to enhance the transient stability where two agents- prediction and control, are used under abnormal operating conditions through the application of potential energy boundary surface (PEBS) method. However, the prediction agent provides some misleading prediction due to the complexities in the real-time operation of power systems.

Decentralized schemes can be used with greater flexibility as these approaches operate based on the local information of the system. Some decentralized approaches based on MAS have been used in [25–27] to improve the transient stability of power systems where the agents act in a coordinated manner. However, decentralized schemes work well when there are weak coupling in power systems which is not the case for smart grids. A MAF provides a more flexible way of increasing both the resiliency and efficiency through the combination of top-down and bottom-up autonomous decision-making intelligence in a distributed environment. A hierarchical distributed MAF has the capability of maintaining interactions among different physical operational processes and agent activities through proper communication [28,29]. The agents in a distributed MAF use the online information and energy flow to communicate with each other and make a decision which could be used in power systems for the coordination of protection devices to enhance the transient stability. However, the hierarchical distributed MAS as proposed in [28,29] are not based on the calculation of CCT. Therefore, a distributed MAF with the utilization of CCT information is more useful for faster and accurate transient stability assessment.

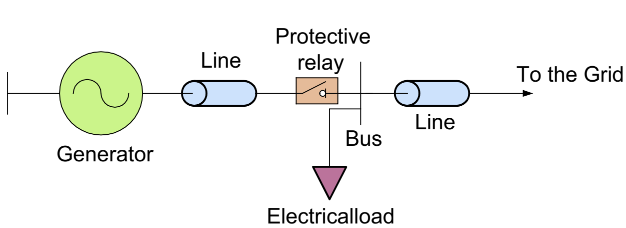

Fig. 1. Typical node in smart grid.

Hybrid approaches for CCT calculation, are the combination of direct or transient energy function and time-domain simulation method, have been widely used for assessing online transient stability of power systems [30–32]. In fact, these methods only consider a fixed set of nominal loads to calculate the CCT though the CCT can be affected adversely due to the variation of loads. Moreover, the information of neighboring systems is not used in [30–32] to calculate the CCT and thus, the calculated CCT with these hybrid approaches has the lack of accuracy. The MAF works based on the information gathered from different parts of power systems because of its distributed characteristics and the application of this framework calculates the CCT with higher accuracy. As a matter of fact, the MAF based on the CCT calculation has been uncovered in the literature of transient stability assessment.

This paper aims to design a multi-agent based architecture to provide a better coordination of protection devices with proper CCT information to improve the transient stability of power systems. The CCT is calculated through the combination of both direct and time-domain simulation method where the fault clearing time is approximated from the direct method and this time is used as starting values for the time-domain simulation method. The designed MAF works based on a protection relay coordination algorithm where each agent in the MAF is equipped with a protection relay. The developed algorithm assists agents to dynamically adapt the online measurement capability which is a significant addition for the online transient stability assessment. This dynamic adaptability provides flexibility to agents for self-reconfiguration in an autonomous way when the characteristics of the system vary. The proposed scheme is verified through simulation results on an IEEE 39-bus system by applying three-phases short-circuit faults at different locations under various loads of generators. A large-scale 16-machine 68-bus power system is also considered to illustrate the potential and adaptability of the proposed approach for three-phase short-circuit faults.

The rest of this paper is organized as follows: Section 2 shows the general concept of MAF for protection systems which includes the agent architecture and smart grid model; the proposed MAF for detecting faults and dynamic adaptability in smart grids is discussed in Section 3; the validation of the proposed scheme is shown in Section 4 with simulations under different contingencies; and finally, this paper is concluded with the findings and further research direction in Section 5.

MAF for protection system

PMUs are used to measure the fault current and line current flow status and monitor the instantaneous load condition of generators. When a fault occurs in power systems, the characteristics of the system change which in turn cause the variation in CCT. In MAF, the agents have direct interaction to incorporate these changes for the calculation of CCT which needs to be used for controlling circuit breakers (CBs). Subsequently, a communication framework is also developed using Java Agent Development Framework (JADE) platform, where agents can communicate with each other in real-time. Through this communication facility, they can cooperate with each other to confirm their operation for proper relay coordination. The multi-agent architecture and smart grid model used in this paper have been discussed in the following subsections.