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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.

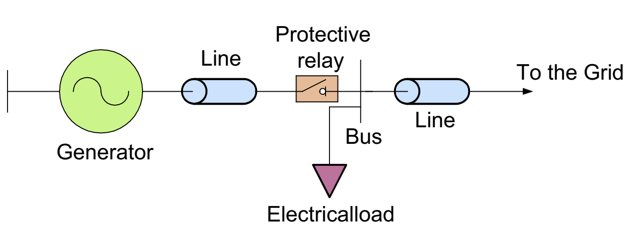

Fig. 1. Typical node in smart grid.

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.

Agent architecture for protection relay

Smart grids use specific protocols and diverse transmission media for monitoring and controlling critical infrastructures [33]. A high level of automation is essential for protective devices due to the decentralization, independency and dynamic characteristics of smart grids [34]. With the advent of global positioning system (GPS) technologies, PMU-based protection schemes are currently used in smart grid automation. In power systems, protection relays (PRs) are installed in a distributed fashion throughout the transmission networks to protect the system from severe physical disturbances such as, faults or sudden load changes which are likely to occur [35]. Power systems become unstable if the fault clearing time of CBs is longer than the CCT and therefore, a robust coordination of PRs is necessary. For the premises of protection system improvement in future smart grid, one of the effective solution is to implement distributed MAFs along with PRs. The MAF is composed of multiple interacting intelligent agents within an environment where the term *'agent'* is used to refer to computer programs used for independent control action of PRs based on events in the surrounding environment. A general framework for agent-based smart grid protection scheme is shown in Fig. 2.

The implementation of PMU-based digital relays helps to utilize the concept of agent-based PRs in smart grid protection systems [36]. Since the agents are equipped with PRs, they simultaneously work together to update the system information at each integration step for any change in system conditions and this promotes their online capability and scalability for protection relay coordination. The functions of these relay agents are implemented through software to provide a thread of control to each CB which gives them with a greater capability to self-check under versatile conditions and this is a significant addition to the protection system. PMUs are used to provide a set of CB status signals among the relay agents to assist in decision making for operating PRs. The agents are dynamically configured to communicate with each other by exchanging status signals. However, in practice, the MAF can be implemented in substation automation with two open international standards- IEC 61850 and IEC 61499 function block executable specification. IEC 61850 protocol is used for open communication among relays within the substations in which IEC61850 GOOSE messages utilize multicast Ethernet to provide a real-time support for protection mechanisms and use for communications among relay equipments [37]. The IEC 61499 is used to encapsulate and implement the intelligent control agent [38].

The general architecture of an agent-based smart grid protection scheme is shown in Fig. 3. In this architecture, the fault current and line current can be measured from full network topology via PMUs, and subsequently, the actual load condition of generators can be monitored from the current status of power generation. The CCT is dynamically evaluated and available to the protection relay agents which is calculated based on the physical disturbances, e.g., faults or sudden changes in loads. At the same time, relay agents are communicating with each other to coordinate the protection relays by simply exchanging their status signals. Since agents have direct interaction with the physical model of power systems, any change in system conditions provides them a flexibility to decide their control action through the developed algorithm. The agents can implement their CB control action based on their perceptions which means that the tripping and reclosing of CBs with corresponding CCT information can be accomplished through agents to improve the transient stability.

In the agent-based relay framework as shown in Fig. 2, the equations related to the PR can be written as [39]

$$\dot{x}_p = f_p(x_p, y_p, r) \tag{1}$$

$$y_p = g_p(x_p, r) \tag{2}$$

$$z_p = h_p(x_p, y_p, r) \tag{3}$$

where x_p and y_p are the internal dynamics of the PR and CB which comprises a set of logic signals depend on the local state variable, e.g., node voltage and current through the relay, r is the relay settings, z_p is the output signal of the PR which acts as an input logic to the CB for opening and closing its contacts. The functions f_p, g_p and h_p are discontinuous since they provide CB operation at any instant of time.

Each agent uses the simple control logic (z_p) along with breaker status signal $C_i(t)$ for breaker i, where $i = 1, 2, 3, \cdots, n$ where n is the number of circuit breakers (CBs) distributively located in smart grids. For the operation of CBs, the control logic with status signals for opening and closing can be initiated as

$$C_i(t) = \begin{cases} 0, & \text{for opening CB at time } t \\ 1, & \text{for closing CB at time } t \end{cases}$$

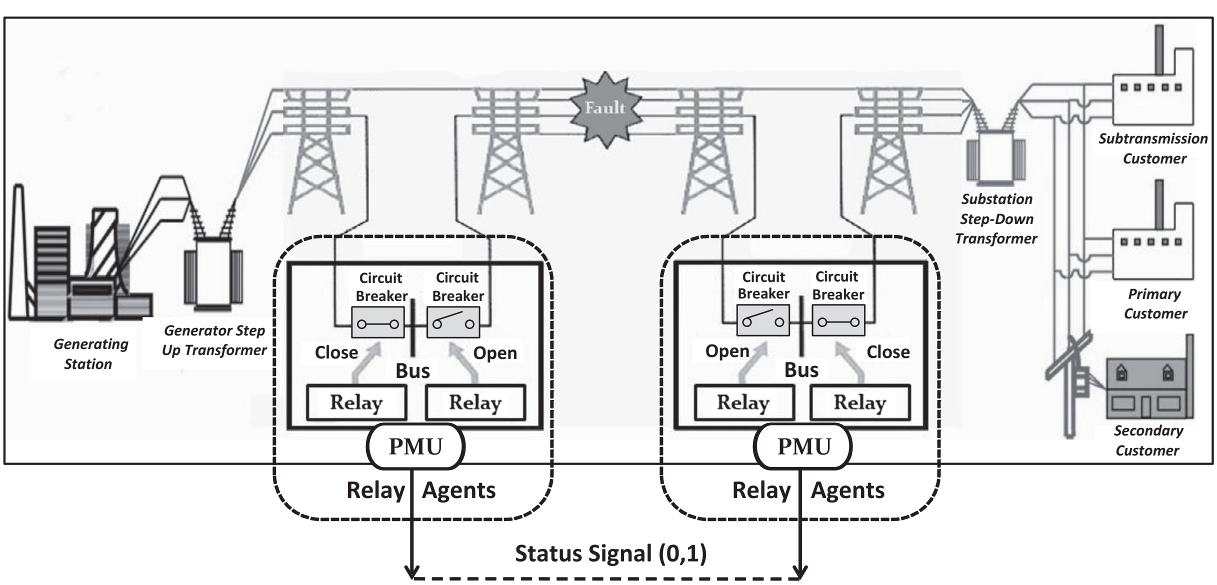

Fig. 2. Agent-based smart grid protection infrastructure.

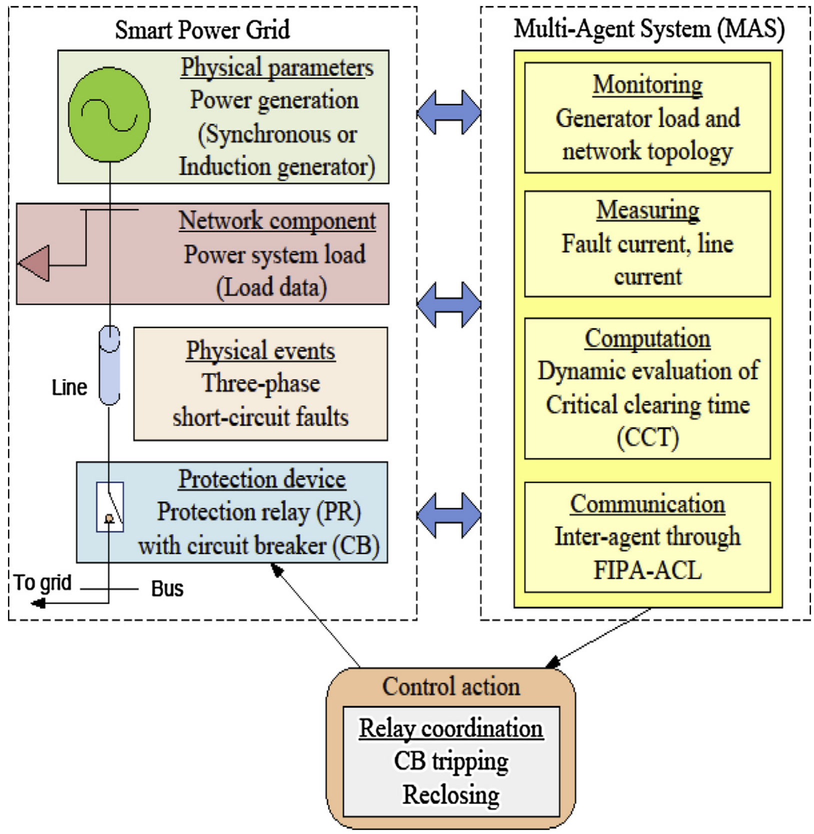

Fig. 3. General architecture for smart grid protection.

Initially at normal operating condition, the breaker status signal is set to 1 when there are no physical disturbances. The entire MAF is developed through the combination of MATLAB and JADE platform. In this infrastructure, the physical model of power systems is developed in MATLAB and the necessary communication network for agents is built in the JADE where a number of equivalent agents are created in accordance with each PR in power systems. The JADE complies with requirements of the Foundation for Intelligent Physical Agent (FIPA) which is a standard organization of IEEE Computer Society for agents and MAS. FIPA provides the agent communication language called FIPA-ACL which is used for agent communication, negotiation and collaboration inside the JADE platform.

Smart grid model

The IEEE 10-machine 39-bus New England test system shown in Fig. 4, which is considerably a large system for assessing transient stability of power systems, is considered in this paper to coordinate the relay operation with the proposed agent-based scheme. This system comprises 39 buses along with 10 generators, 19 loads totalling 6150.1 MW and 1233.9 MVAr of real and reactive power, respectively. All generators are modeled as a third-order synchronous generator with IEEE type-2 exciter except generator at bus 31 which is arbitrarily considered as a slack bus. A simple turbine governor is used for each generator except generator 1. The details of the system data can be found in [40,41]. The power system is modeled as a set of nonlinear differential and algebraic equations as [42]

$$\dot{x} = f(x, y, z) \tag{4}$$

$$0 = g(x, y, z) \tag{5}$$

where x is the state variable $x \in \Re^n$, y is the algebraic variable $y \in \Re^m$, z is the vector of system parameters $z \in \Re^l$, f is the differential equations $f : \in \Re^n \times \in \Re^m \times \in \Re^l \to \in \Re^n$, g is the algebraic equations $g : \in \Re^n \times \in \Re^m \times \in \Re^l \to \in \Re^m$.

In this paper, the third-order synchronous generator model is used in a representation of the voltage behind direct-axis transient reactance and can be written as [41]

$$\dot{\delta} = (\omega_i - \omega_{0i}) \tag{6}$$

$$\dot{\omega}_i = -\frac{D_i}{2H_i}(\omega_i - \omega_{0i}) + \frac{\omega_{0i}}{2H_i}P_{mi} - \frac{\omega_{0i}}{2H_i}\left(E'^2_{qi}G_{ii} + E'_{qi}\sum_{j=1}^{n}E'_{qj}B_{ij}\sin\delta_{ij}\right) \tag{7}$$

$$\dot{E}'_{qi} = -\frac{1 + (x_{di} - x'_{di})B_{ii}}{T_{d0i}}E'_{qi} + \frac{x_{di} - x'_{di}}{T_{d0i}}\sum_{j=1}^{n}E'_{qj}B_{ij}\cos\delta_{ij} + \frac{1}{T_{d0i}}E_{fi} \tag{8}$$

where the subscript i represents the synchronous generator connected to ith bus, δ is the power angle, ω is the rotor speed, ω_o is the synchronous speed, H is the inertia constant, P_m is the mechanical input power, D is the damping constant, E'_q is the quadrature-axis transient voltage, E_q is the quadrature-axis voltage, T_{do} is the direct-axis open-circuit transient time constant, E_f is the equivalent voltage in the excitation coil, x_d is the direct-axis synchronous reactance, x'_d is the direct-axis transient reactance, G_{ii} and B_{ii} are the self-conductance and self-susceptance of ith line, respectively, G_{ij} and B_{ij} are the conductance and susceptance between ith and jth lines, respectively, $\delta_{ij} = \delta_i - \delta_j$ is the power angle deviation between ith and jth lines, I_d and I_q are the direct-axis and quadrature-axis currents, respectively.

The whole system as shown in Fig. 4 is divided into four zones for simplicity and each zone provides independent breaker control operations. The zoning of IEEE 39-bus system can be seen in Fig. 4 and summarized as follows:

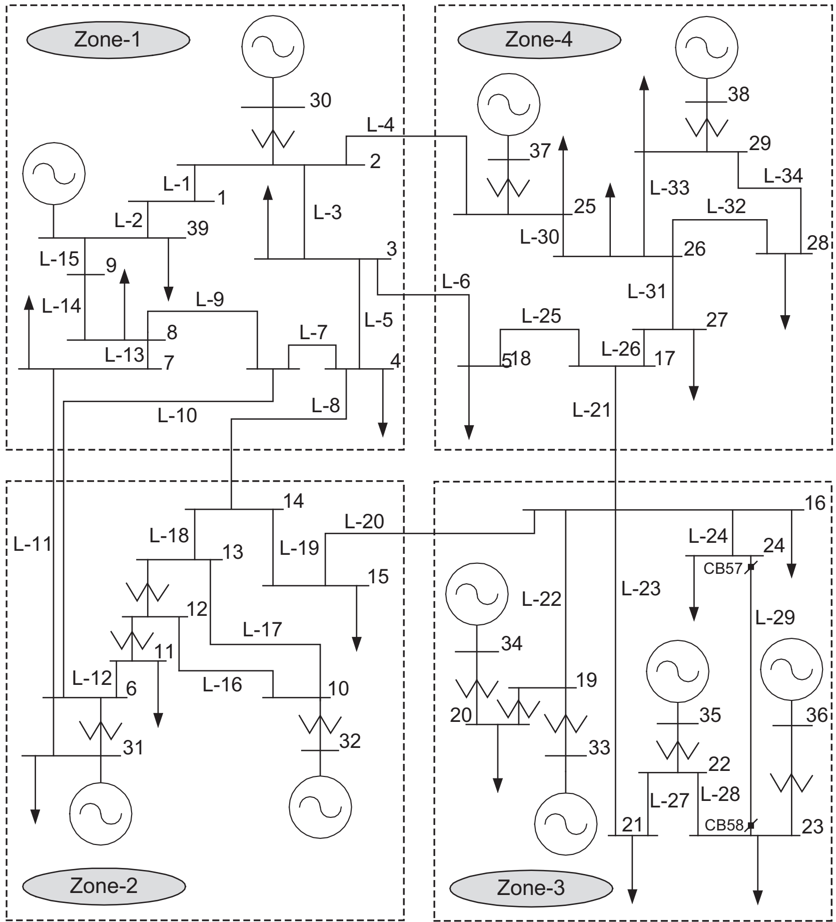

Fig. 4. Single line diagram of IEEE 39-bus New England test system.

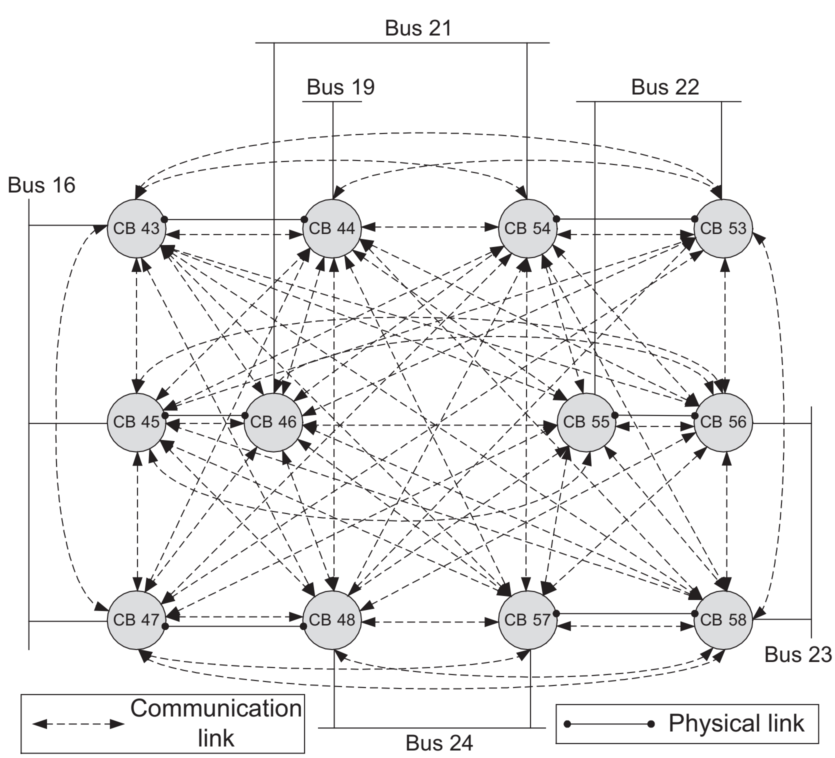

Fig. 5. Network diagram for relay agents in zone 3.

- Zone 1: Generators at bus-30 and bus-39; and loads at bus-3, bus-4, bus-7, bus-8, bus-39.
- Zone 2: Generators at bus-31 and bus-32; and loads at bus-11, bus-15, and bus-31.
- Zone 3: Generators at bus-33, bus-34, bus-35, and bus-36; and loads at bus-16, bus-20, bus-21, bus-22, bus-23, and bus-24.
- Zone 4: Generators at bus-37 and bus-38; and loads at bus-18, bus-25, bus-26, bus-27, bus-28, and bus-29.

These zones are interconnected through seven lines: Zone 1 and Zone 2 are connected through lines L-8 from bus-4 to bus-14, L-10 from bus-5 to bus-6, and L-11 from bus-7 to bus-31; Zone 2 and Zone 3 through line L-20 from bus-15 to bus-16; Zone 3 and Zone 4 through line L-21 from bus-16 to bus-17; and Zone 1 and Zone 4 through lines L-4 from bus-2 to bus-25 and L-6 from bus-3 to bus-18. There are numerous PMU-based relays deployed within this IEEE 39-bus system. The agents are located along with PRs in each zone. In this work, the main attention has been paid on Zone 3 to evaluate the performance the proposed scheme and the block diagram of communication networks for all breaker agents within this zone is shown in Fig. 5. In this network, they can communicate with each other in real-time in a two-way communication fashion. In this figure, the arrow with dashed line indicates a two-way communication link among all relay agents whereas the solid line represents the physical link, i.e., transmission line among them. Since communication is the heart of the proposed MAF scheme, the communication protocol of agents among different zones of IEEE 10-machine 39-bus power system is shown in Fig. 6. However, the communication diagrams among the various relay agents in each zone are not indicated in Fig. 6 since they have similar network diagram of Zone 3. A three-phase short-circuit fault is considered in the transmission line between two nodes where the agents are communicating with the neighboring one.

Proposed multi-agent scheme

In the proposed multi-agent scheme, the agents use an algorithm which provides them a capability to simultaneously monitor and measure the current status of the system. With this feature, the agents have full flexibility to deal with the versatile system conditions under different contingencies. The proposed algorithm is implemented in each agent so that it can provide a full thread of control to the corresponding PR for controlling CB. The flow chart of the proposed algorithm is shown in Fig. 7. The detail activities of different parts of the proposed scheme are described in following subsections.

Fault detection and identification

Power systems exhibit continuously changing characteristics and faults as well as outages are most likely to occur within the system. In such cases, effective fault detection and its diagnosis can improve the reliability and stability of power systems. The Fault diagnosis comprises of detecting a fault along with its location and isolating the faulted portion from the remaining network. The current (I_R) across the relay can be obtained by current transformer and can be written as

$$I_R = \frac{V_s - V_r}{Z_T} \tag{9}$$

where V_s is the sending end bus voltage, V_r is the receiving end bus voltage and Z_T is the total impedance of the system. In the proposed MAF, the following expressions are used for short-circuit fault detection and identification.

$$I_f = \begin{cases} I_R > I_{TH}, & \text{Fault detected} \\ I_R < I_{TH}, & \text{No fault} \end{cases}$$

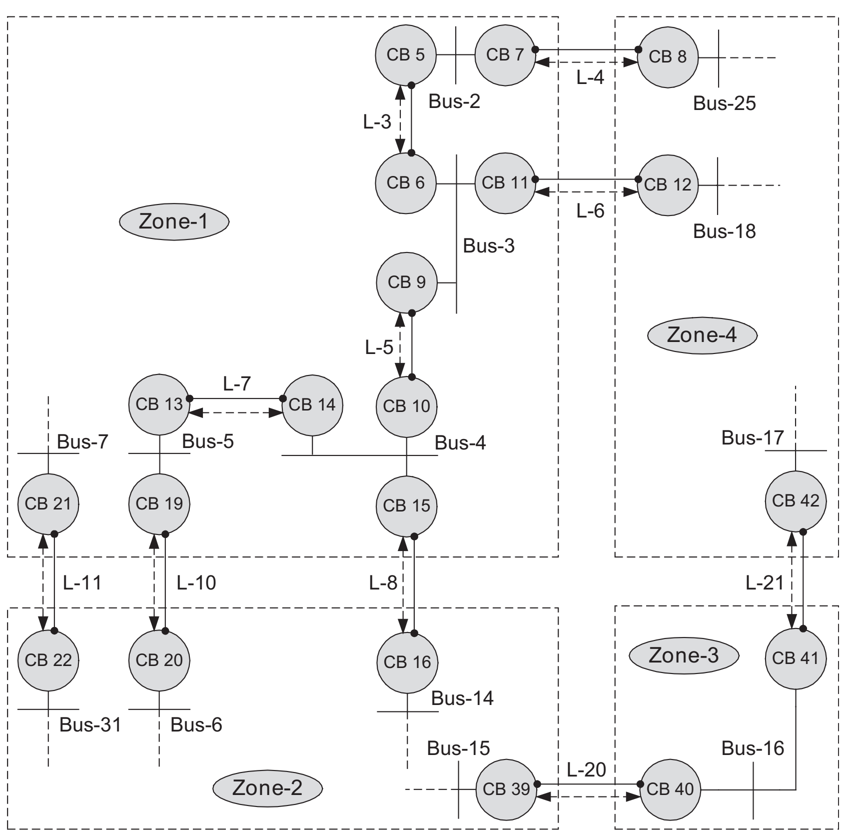

Fig. 6. Communication diagram for different zones of IEEE 39-bus power system.

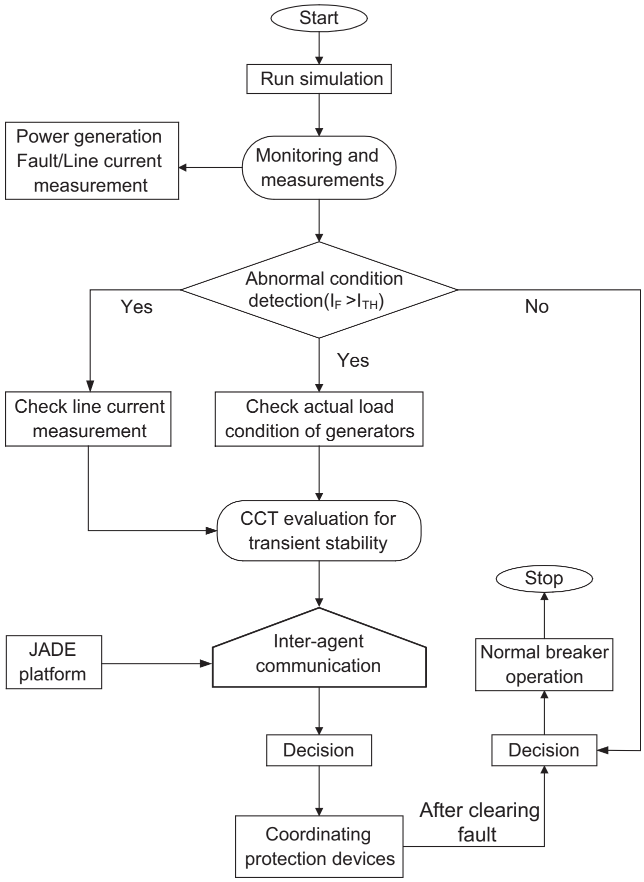

Fig. 7. Flow-chart of proposed approach.

$$I_L = \begin{cases} Status \rightarrow 1, & \text{Current flows} \\ Status \rightarrow 0, & \text{No current flows} \end{cases}$$

From the first expression it can be revealed that, a threshold value of the current, I_{TH}, is set for each relay for precise fault detection. When a three-phase short-circuit fault occurs in a particular branch, it can be detected by measuring the fault current, I_f. Agents can recognize a fault when current, I_R, across the relay flows above the pre-defined threshold value, I_{TH}, set for that relay, i.e., $I_R > I_{TH}$, and the agents take the decision for controlling CBs. On the other hand, if there are no faults, the current across the relay, I_R, flows below the threshold limit and the agents take the decision for normal CB operation. At the onset of the fault, the second expression is used to identify the fault location. The proposed approach checks the line current measurement look up table at each iteration. This look up table consists of line current, I_L, which is measured from each branch indicating flow and no flow statuses as '1' and '0', respectively. Using this table, the proposed scheme is capable to determine the recent current flows status in a branch. It stores a set of data in a vector for first iteration and compares it to the same vector obtained from the next iteration. If the subtraction of two vectors in all branches becomes zero then there is no change in line current flows since last iteration. On the other hand, if a non-zero vector appears in a particular branch, the approach can detect a change in the line current, i.e., no current flows on that branch and hence, identify the out-of-service line in a network.

Dynamic adaptability

When the loads change, the generator output power will change and the generators connected to the nodes simultaneously picked up the extra amount of loads since stable operation requires a continuous balance between the energy input to the prime movers and the electrical load of the system. For checking the actual load conditions of generators, the proposed approach first monitors the present nominal load (P_G) of the generators. If the current load condition is similar to the nominal load, the CCT is calculated for this. If the load of generators has changed, the proposed MAF is able to dynamically adapt to this change in load conditions, i.e., the new load condition (P'_G). This can be summarized as follows

$$\begin{aligned} & P_G = P^{\circ}_G \text{ (for normal operation)} \\ & \text{if } P_G > P^{\circ}_G \text{ and } P_G < P^{\circ}_G \ (P^{\circ}_G \pm \% \text{ load change}) \\ & P'_G = P_G \text{ (for new load)} \\ & \text{else } P_G = P^{\circ}_G \text{ (for given load)} \end{aligned}$$

where P°_G is the generator input mechanical power. After gathering the current load information of generators, the corresponding new CCT is calculated to provide it to the relay agents.

CCT calculation

For CCT calculation, the combination of both direct and time-domain simulation method is used in this paper. The reason for using a combination of both methods is that the direct method is faster but it has less accuracy and adaptability to the model for over simplification, whereas the time-domain simulation approach is slow for large-scale power systems but it is more accurate. In the proposed multi-agent approach, the fault start and end time, initial values of the estimated minimum and maximum fault clearing times, and time-domain simulation step-size are set up first. The initial values of the estimated CCT are determined through the direct method. A load flow analysis is then performed for initial conditions as well as pre-fault condition and the transient stability with time-domain simulation is evaluated using dynamic equations of power systems. The stability is then checked based on the simulation result and the CCT calculation is successful when the system is stable for minimum fault clearing time and unstable for that of maximum. In the designed MAF, the load flow analysis and CCT calculation are performed in MATLAB and then integrated with JADE for coordinating the relays in physical power systems. As the proposed scheme updates the measured information at each integration step to compute the CCT for current load conditions, the system relies on a continual stream of online CCT information which enhances the online capability and scalability of agents.

CB operation

Once the CCT information is obtained, agents start to negotiate and communicate with neighboring agents to control the breaker operation. It is noted that the CCT information for a fault in a particular branch is available to the corresponding CB of that branch. Agents coordinate the protective relays by opening CBs before the corresponding CCT and reclosing them quickly after the clearance of faults. For breaker operation, a set of status signals is used. Once a fault occurs, agents initiate the signal $C_i(t) = 0$ to open the corresponding CBs before the CCT to remove the faulted portion from the rest of the system. At the same time, they send this status signal to the neighboring agents to confirm their operation during an outage and subsequently, they receive a same confirmation message from those agents. When the fault is cleared after a certain duration they initiate $C_i(t) = 1$ for reclosing the CBs to reconnect the line.

During the entire process, the agents perform the following steps to communicate with each other for the proper coordination of protection devices.

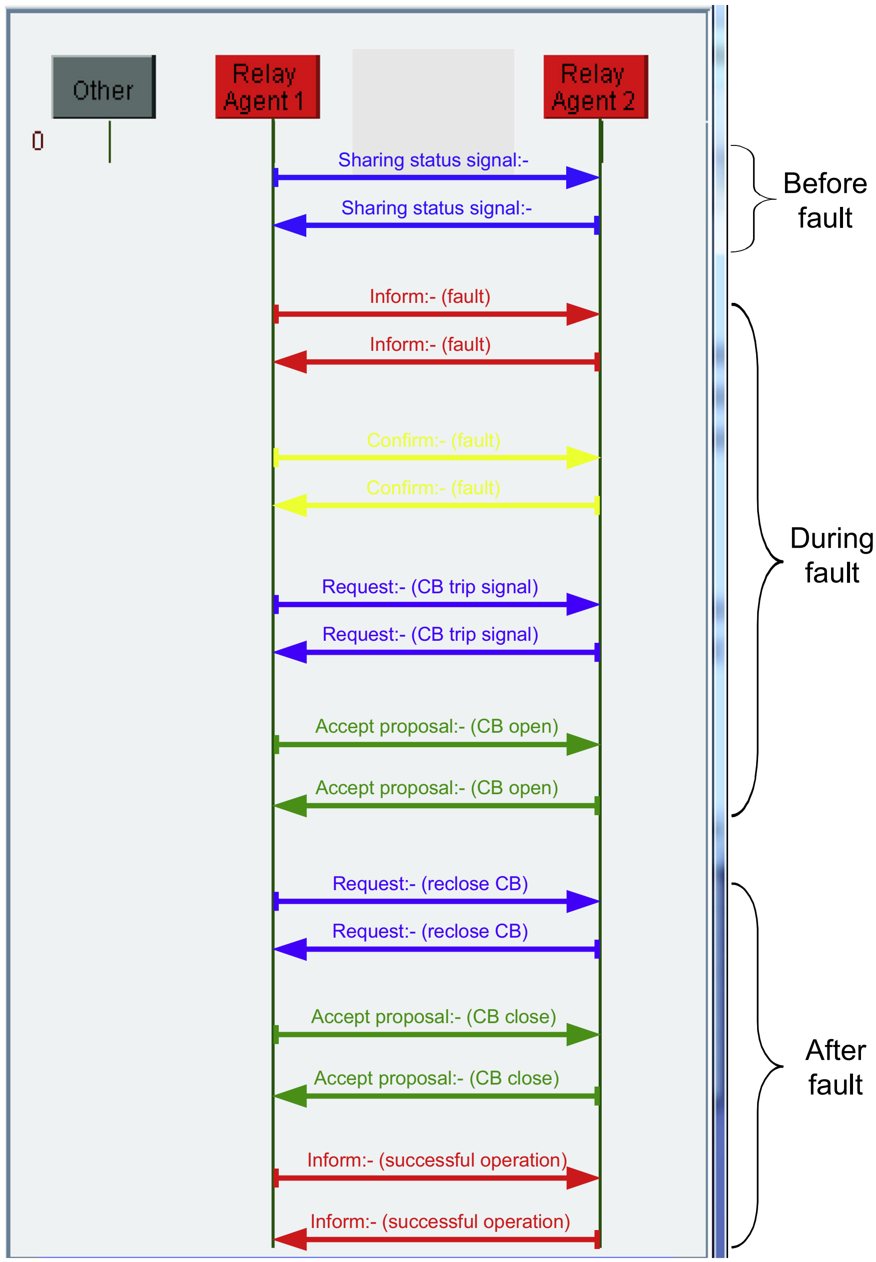

Fig. 8. Relay agent coordination in JADE platform.

a. Share status signals to continuously monitor the entire network and do not take any actions before any undesirable events.
b. Inform other agents about events such as, faults or sudden changes in loads.
c. Confirm the occurrence of events with other agents.
d. Obtain the CCT information required for tripping and reclosing the breakers.
e. Request other agents to trip the breakers within the CCT.
f. Accept-proposal for tripping the breakers.
g. Request other agents to reclose the breakers after clearing the fault.
h. Accept-proposal for reclosing the breakers.
i. Inform other agents of the successful operation.

The sequence of protection relay coordination is graphically shown in Fig. 8 which is developed in the JADE platform. From Fig. 8, it can be seen that relay agents perform two-way communication for each step of message transfer between them.

Simulation results

In this section, agents' ability in the developed MAF is demonstrated to coordinate the protection devices for detecting and isolating faults with corresponding CCT information. The proposed distributed MAF framework is employed through MATLAB and JADE to validate the simulation results. At first, it is considered that IEEE 39-bus test system shown in Fig. 4 operates normally at steady-state condition and all branches are in service. The summary of the analysis including CCT information for faults at different locations under various load conditions, current measurements look up table, and network line flows for different zones are shown in Tables 1–3. Table 1 summarizes the dynamic evaluation of the CCT information through transient simulation at each zone for nominal load condition of generators and with 5% changes in loads, i.e., with the increase in loads of 5% in all generators. From Table 1, it can be seen that the CCT varies with changes in loads of generators and decreases under heavier load conditions which means that the stability margin of the system is being reduced. Table 2 shows the line current measurement look up table for the lines which are affected by faults along with their statuses. Table 3 indicates network line flows at different zones before and after faults.

Table 1
Effect of load changes in generators on CCT for IEEE 39-bus system.

Case	Location	Line trip	Critical clearing time (ms)	
			Given load	5% Load change
1	Zone 1; Line 3	2–3	269	263
2	Zone 2; Line 12	6–11	240	236
3	Zone 3; Line 23	23–24	251	243
4	Zone 4; Line 29	25–26	216	211

Table 2
Current measurement look up table.

Current measurement	Line	Status	Current measurement	Line	Status
1	3	1	5	23	1
2	3	1	6	23	1
3	12	1	7	29	1
4	12	1	8	29	1

Table 3
Network line flows at different zones before and after fault.

Location	Line	From bus	To bus	Line flow status	
				Before fault	After fault
Zone 1	3	2	3	1	0
Zone 2	12	6	11	1	0
Zone 3	23	23	24	1	0
Zone 4	29	25	26	1	0

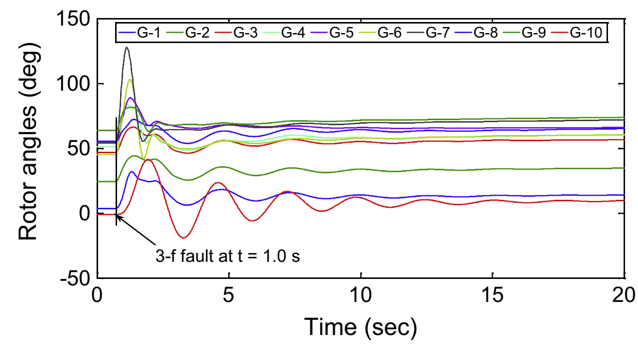

Fig. 10. Generator rotor angles response at nominal load condition.

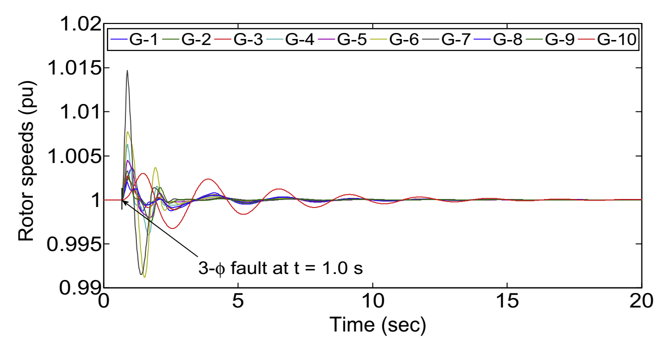

Fig. 11. Generator rotor speeds response at nominal load condition.

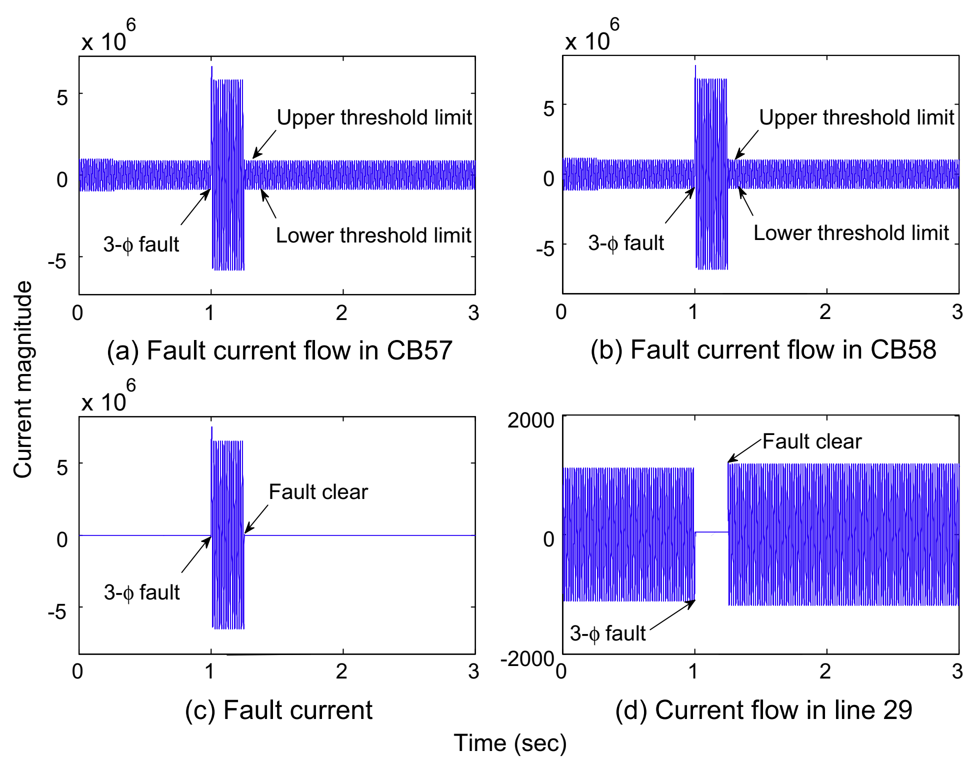

Fig. 9. Current flows (a) in CB 57, (b) in CB 58, (c) for fault, and (d) in line 29.

In this paper the following four case studies are considered to illustrate the performance of the designed MAF scheme:

- Performance evaluation for faults at nominal capacity of generators.
- Performance evaluation for faults with increase in loads of generators.
- Performance evaluation for faults between different zones.
- Performance evaluation for faults at large-scale power system.

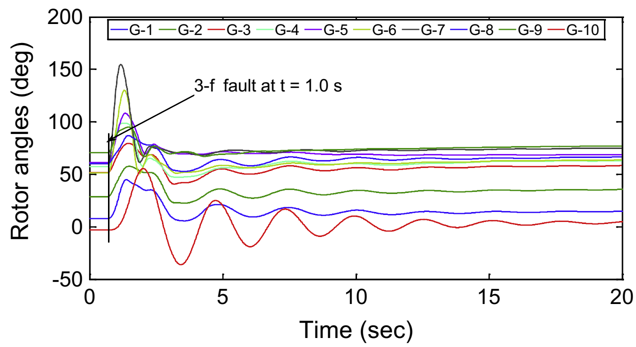

Fig. 12. Generator rotor angles response at 5% load changes.

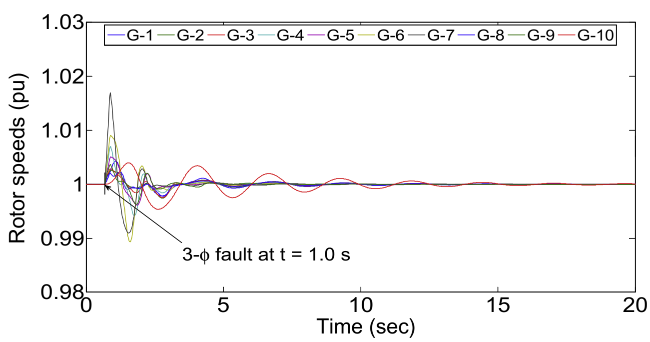

Fig. 13. Generator rotor speeds response at 5% load changes.

Performance evaluation for faults at nominal capacity of generators

To evaluate the performance of the designed MAF, case-3 in Table 1 is considered in this paper. This case study involves a three-phase short-circuit fault applied at $t = 1.0$ s at transmission line 29 connecting bus-23 and bus-24 under nominal load condition. As a result, the behavior of the current has changed across the relays, i.e., suddenly increased. Since a pre-defined threshold value of fault current is set in each relay protecting corresponding line, the relay agents detect the fault from the current flows which is above the threshold value. Fig. 9(c) shows the fault current and the corresponding flows across the relays for line 29 in CBs 57 and 58 (as indicated in Fig. 4) are shown in Fig. 9(a) and (b), respectively. At the same time, the proposed approach also checks the line current measurement look up table which is summarized in Table 2 to find inconsistencies between previous and recent

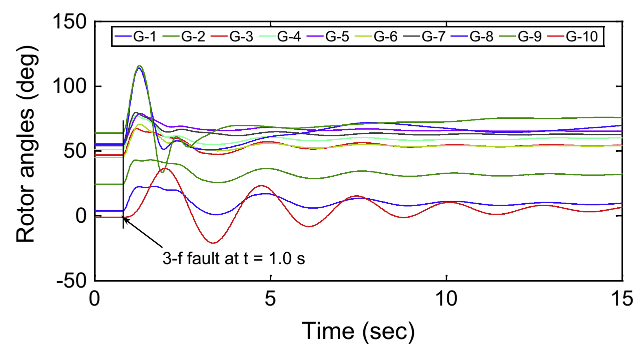

Fig. 15. Generator rotor angles response for fault at line 4 between Zone 1 and Zone 4.

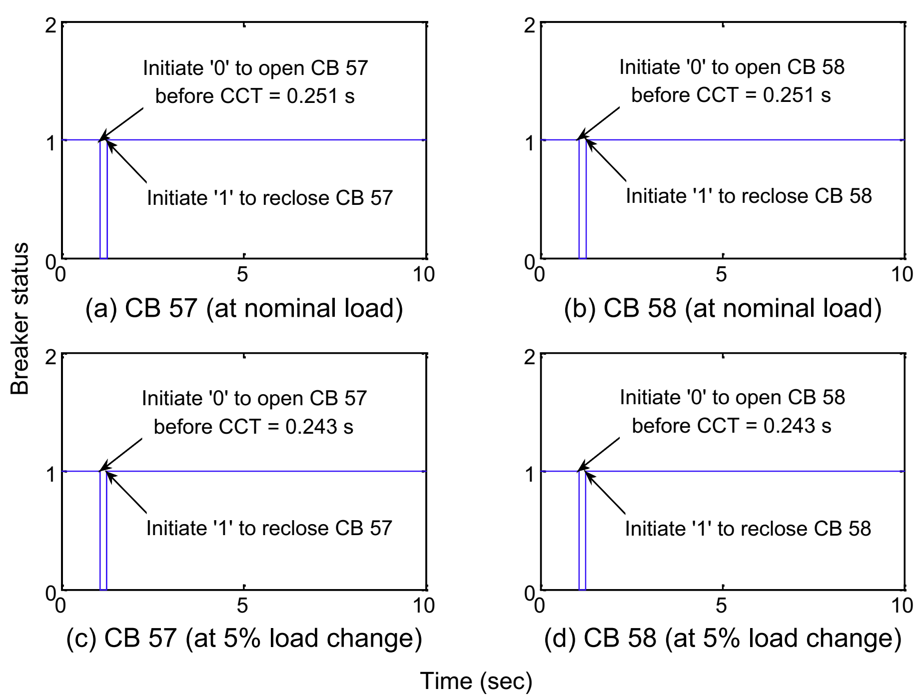

Fig. 14. Breaker statuses for nominal and 5% load change.

iterations. From Table 3 it is seen that, before fault the line current flows from bus-23 to bus-24 is '1' whereas it appears '0' after the occurrence of faults at line 29. In addition, from Fig. 9(d) it can be seen that the current flows through line 29, i.e., between bus-23 and bus-24 is zero until the fault is cleared through agents' action. Once a fault is identified, the corresponding CCT

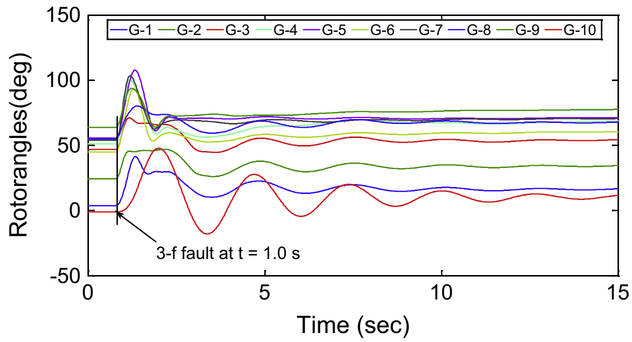

Fig. 16. Generator rotor angles response for fault at line 20 between Zone 2 and Zone 3.

information is dynamically evaluated which is 251 ms for nominal loads of generators. Using this CCT information, the agents coordinate the protection relays by initiating the status signal $C_i(t) = 0$ to open the corresponding CBs 57 and 58 to remove the faulted line before the CCT. At the same time, inter-agent communication takes place to ensure the proper operation of relay agents with the corresponding CCT information.

Fig. 10 shows the rotor angles of the generators from where it can be seen that the rotor angles start to oscillate from $t = 1.0$ s when a three-phase short-circuit fault is applied. The angle oscillations continue until the fault is cleared before the corresponding CCT, i.e., 251 ms. They are found transiently stable over the period of 20 s following the removal of the fault from the rest of the system by tripping the line 29 through successful relay coordination by agents. Consequently, Fig. 11 shows the generator rotor speed profoundly over the period of 20 s from where it can be seen that the rotor speeds are stable till 1.0 s and start to oscillate after experiencing faults within the system. After a successful relay coordination through the agents, the speeds are found transiently stable while they return to their original synchronous speed value, i.e., at 1 pu as seen from Fig. 11. Subsequently, when the fault is cleared the agents initiate the status signal $C_i(t) = 1$ to reclose the breakers quickly to reconnect the line.

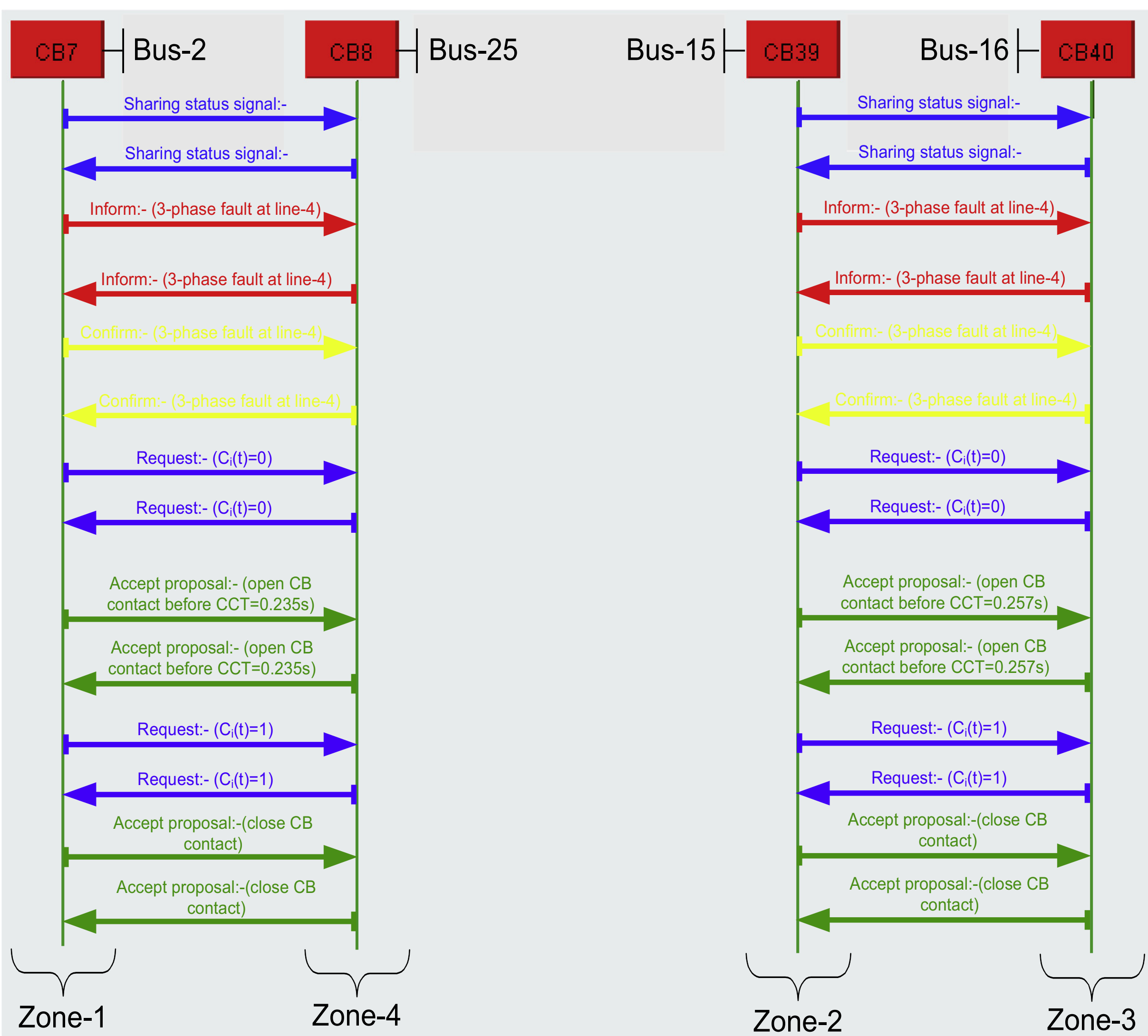

Fig. 17. Agent communication protocol in JADE platform.

Performance evaluation for faults with 5% increase in loads of generators

The same analysis is conducted for a three-phase fault at line 29 with 5% changes in loads, i.e., with 5% increase in loads to all generators. The proposed scheme dynamically adapts to these changes in loads of generators with the logic demonstrated to determine the present load condition for evaluating the corresponding CCT information. In this case, the calculated CCT is 243 ms and the simulation results of generator rotor angles and speeds are shown in Fig. 12 and Fig. 13, respectively. From these figures it can be seen that, the rotor angles and speeds are transiently stable following the removal of the fault from the system by tripping the line 29 before the new CCT. This means that the agents successfully coordinate the corresponding breaker operation with the new CCT information, i.e., 243 ms for the transient stability improvement. The corresponding CBs 57 and 58 statuses for both nominal and 5% changes in load are shown in Fig. 14 and it can be seen that the breakers continue their operation with status ‘1’ until 1.0 s. When a fault is applied at 1.0 s relay agents initiate ‘0’ and their statuses go to ‘0’ to open the breaker contacts before the corresponding CCTs and return to ‘1’ again by reclosing the breakers in order to reconnect the line. From this case study, it can be revealed that the agents are flexibly coordinating the corresponding CB operation with the new CCT information in order to enhance the transient stability of the system in a smarter way.

Performance evaluation for faults between different zones

To evaluate the performance of the proposed MAF scheme, three-phase short-circuit faults are applied in between the connecting lines of different zones. A fault is applied at $t = 1.0$ s in line 4 between bus-2 and bus-25 connecting Zone 1 and Zone 4 and another one is applied at the same time at line 20 between bus-15 and bus-16 connecting Zone 2 and Zone 3. The agents properly cooperate and communicate with each other and hence, the PR coordination occurs successfully. In this case, the CCTs are found 235 ms and 257 ms, respectively, and the generator rotor angles for both fault scenarios are shown in Fig. 15 and Fig. 16, respectively. Also, the agent communication protocol in JADE platform among different zones for both the fault scenarios is graphically presented in Fig. 17.

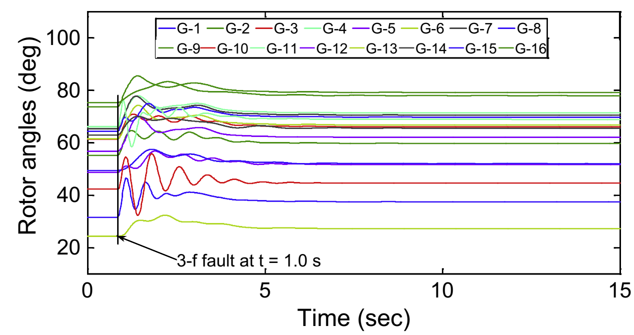

Fig. 19. Generator rotor angles response for fault at line between bus-33 and bus-34.

Performance evaluation for faults at large-scale power system

To illustrate the potential of the proposed agent-based scheme in a large-scale power system, a benchmark 16-machine 68-bus

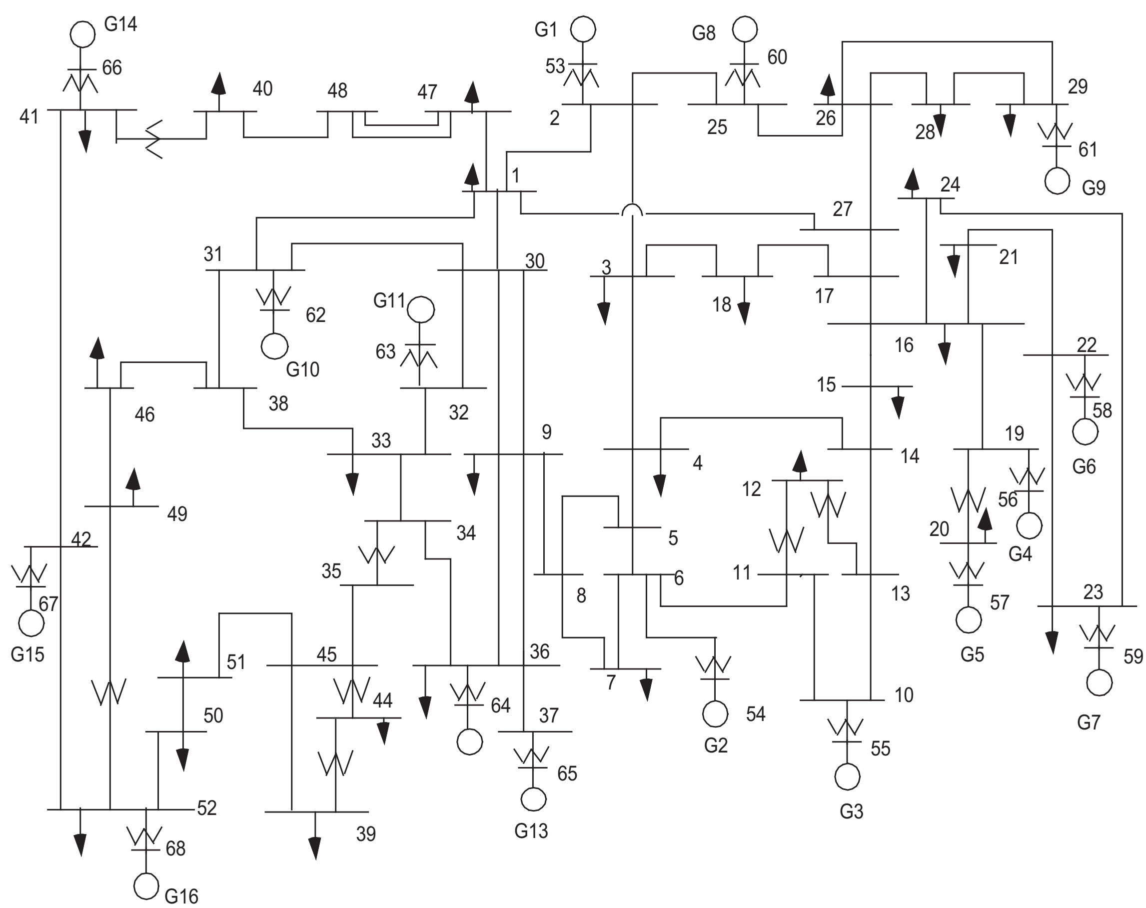

Fig. 18. Single line diagram of 16-machine 68-bus power system.

power system is used. The single line diagram of the system is shown in Fig. 18 and details of the test system can be seen in [43]. A three-phase short-circuit fault is applied at t = 1.0 s in the line between bus-33 and bus-34 with nominal generation capacity of generators. The CCT is found as 142 ms and the rotor angles of the generators are shown in Fig. 19 over the period of 15 s, from where it can be seen that, agents potentially perform their tasks to efficiently coordinate the relays in order to enhance the transient stability of large-scale power systems.

Conclusion

The designed MAF provides a powerful framework for enhancing the transient stability of power systems under different operating conditions. The designed scheme has been used to demonstrate the capability of adapting system configurations through proper relay coordination within the calculated CCT. The designed MAF also provides a robust environment for faster and accurate transient stability assessment and more stability margin. From the simulation results, it is clear that the transient stability of power systems is adversely influenced due to the changes in loads which in turn have a vital impact on the evaluation of CCT. In the designed MAF, the individual agent has the capability to analyze and understand any physical disturbance within the system and initiates appropriate control action through PRs to open or close CBs. The agents also monitor the condition of power grids in a smarter way through intelligent decision making based on the designed algorithm and when a fault occurs they cooperate and communicate with each other to detect and isolate it precisely with the corresponding CCT information. Different large-scale test systems are used to evaluate the effectiveness and performance of the proposed approach. The future work will deal with the design of such type of agent-based framework for large power systems with the integration of renewable energy sources. Future work will also deal with the implementation of this agent-based model to enhance the transient stability for high penetration of renewable sources into the grid.

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