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Implementation of an Intelligent Grid Computing Architecture for Transient Stability Constrained TTC Evaluation

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Abstract – An intelligent grid computing architecture is proposed and developed for transient stability constrained total transfer capability evaluation of future smart grid. In the proposed intelligent grid computing architecture, a model of generalized compute nodes with 'able person should do more work' feature is presented and implemented to make full use of each node. A timeout handling strategy called conditional resource preemption is designed to improve the whole system computing performance further. The architecture can intelligently and effectively integrate heterogeneous distributed computing resources around Intranet/Internet and implement the dynamic load balancing. Furthermore, the robustness of the architecture is analyzed and developed as well. The case studies have been carried out on the IEEE New England 39-bus system and a real-sized Chinese power system, and results demonstrate the practicability and effectiveness of the intelligent grid computing architecture.

Keywords: Grid computing, Transient stability, Total transfer capability, Generalized compute node, Smart grid

1. Introduction

Nowadays, power systems have become more and more complex with the constant expansion in power system due to the growth in load demand and the continuous upgrade of equipment, such as installations of FACTS devices and integrations of new HVDC linking into existing AC grids. On the other hand, the introduction of the deregulated and unbundled power market operational mechanism, together with present changes in new and emerging generation sources including connections of large renewable energy generation like large wind power with intermittent feature in nature, has further increased the complexity and uncertainty for power system operation and control. As a result, it is likely that power systems will be operated under increasingly stressed conditions, which may lead transmission systems to running closer to their operating limits. Thus, the critical dynamic behavior and the stability issues are posing great challenges to the operation of currently interconnected power systems [1]. Therefore it is much more important for power systems to maintain an adequate security level and achieve appropriately secure operation based on a stability criterion. Accordingly, how to evaluate the total transfer capability (TTC) [2] of power systems rapidly and accurately becomes one of key issues in power engineering. So far, a lot of literature have been published in effective evaluating the TTC. They mainly belong to the deterministic method and the probabilistic method [3, 4]. Although the probabilistic theory based method can reflect the real operating situation of system better, the practical applications are hard to be carried out in the near future. For the deterministic method, the optimization technique based models are widely used in the TTC evaluation [5], [6]. Applying Optimal Power Flow (OPF) technique to the TTC evaluation can take into account all kinds of constraints and control variables conveniently and easily. The computing robust and results, however, are hard to fulfill for on-line applications. Furthermore, some works [7, 8] reported more practical solutions with combination of Continuation Power Flow (CPF) method. Thousands of time domain simulations to determine the transient stability (TS) before dispatching have hitherto been running, which still couldn't meet the demand of the future smart grid. As rapid development of hardware and software technologies of high performance computing, it implies the potential applicability of grid computing which can provide a good opportunity for the solution of future smart grid TTC evaluation taking TS constraints into consideration.

Moreover, a series of existing information and automation systems mainly implementing the supervisory control and analysis of power grid operating condition have been well established and utilized in utility companies around the world. Nevertheless, in most cases, the information in each organizational 'silo' is not easily (even not) accessible to applications and users in other functional units due to different providers and ladder of management.

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Particularly, there exist a lot of idle resources (e.g. a kind of compute nodes with certain computing capacity) in different utilities. These idle resources are hard to be fully taken advantage of in existing operating mechanism of information technology (IT) support platform. With the advent of the smart grid [9-15], the existing IT support platform has to confront many challenges. In the smart grid era, the question to be considered is: can the grid computing offer new solutions to support the collaboration among multiple tasks and the real time and online interoperability and scalability of IT resources?

In this paper, a task level based intelligent grid computing architecture, a model of generalized compute nodes with "able person should do more work" feature for TS constrained TTC evaluation with respect to a specified contingency set is presented to better meet the requirements in the future smart grid and augment the computing capability of existing IT support platform further. Besides, the dynamic scalability and fault-tolerance of the proposed intelligent grid computing architecture are analyzed as well. Finally, the case studies on the IEEE New England 10-machine 39-bus system and a real-sized Chinese power system are conducted to demonstrate the practicability and effectiveness of the architecture.

This paper is organized as follows. Section 2 details the computing flow of TS constrained TTC evaluation. In Section 3, a task level based intelligent grid computing architecture is designed and implemented. The dynamic scalability and fault-tolerance of the architecture are discussed in Section 4. Section 5 shows the preliminary results. Finally the conclusions are summarized in Section 6.

2. Computing Flow of TS Constrained TTC Evaluation

The main aim of TS constrained TTC evaluation is to provide system security margin under certain load-generation increasing pattern with respect to a usual or a critical contingency set. The calculation of the system security margin is based on a given power transfer or generation-load increasing mode. A power transfer is defined as a set of power flow dispatches in which the generation and/or loads are changed to meet specific system dispatch conditions. The corresponding computing flow chart of TTC evaluation with TS constraints is given in Fig. 1. The figure corresponds to a specified power transfer and one contingency, and the final stability limit is the smallest of the limits found for all contingencies.

The time domain simulation method and a power angle-based transient stability index [15, 16] are jointly employed to implement the TS constrained TTC evaluation. The index η is defined as in (1) in the system:

$$\eta = \frac{360 - \delta_{\max}}{360 + \delta_{\max}} \times 100 \qquad (1)$$

where $\delta_{\max}$ is the maximum angle separation of any two generators at the same time in the post-fault response. $\eta>0$ and $\eta\leq 0$ correspond to stable and unstable conditions, respectively.

From the flow chart as shown in Fig. 1, it is necessary for the TTC evaluation with TS constraints to make required iterations corresponding to the critical/ specified contingency set. Yet it is inefficient to implement the online application for the TTC evaluation using the conventional parallel computing technology for the contingency set. Consequently, the application grid computing technology with the characteristics of integrating the computing power of possible computing resources in Intranet/Internet and improving the whole system calculating speed in evaluating TTC with TS constraints considered would be a feasible or even the best solution for a smart grid.

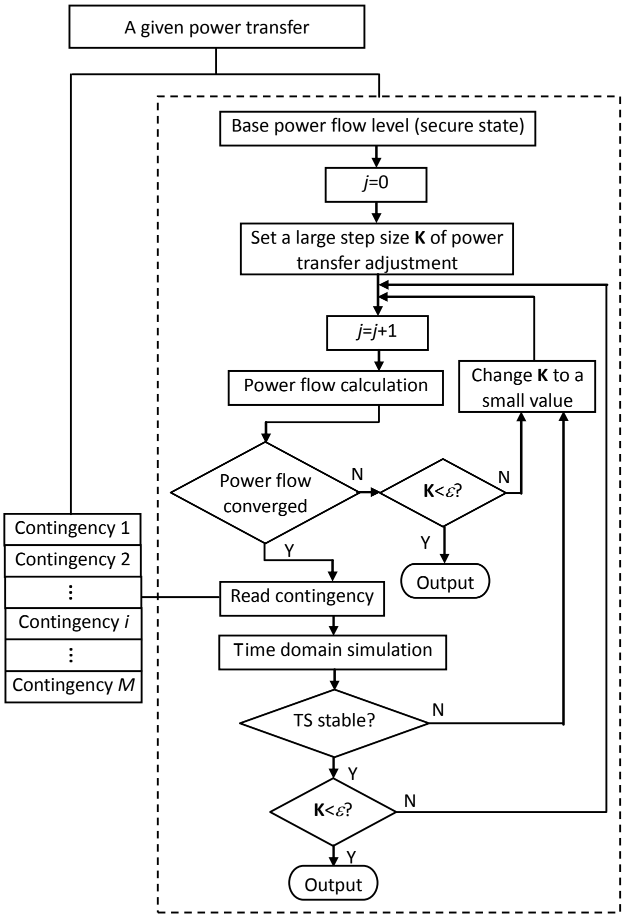

Fig. 1. Computing flow chart of TTC evaluation with TS constraints

3. Task Level Based Intelligent Grid Computing Architecture

In general, the conventional parallel computation solutions can be categorized as multi-processor parallel computation and distributed parallel computation. The former runs in a single machine with multiple CPUs support. Albeit the computing performance of this machine can be exerted to the most, the other computing resources can't be utilized to some extent. In other words, the extendibility of multi-processor parallel computation is not good enough in a distributed computing environment. As for the distributed parallel computation, the well-known PC cluster based high performance computing model is widely used in current power system calculation. In accordance with the well-known PC Cluster [17] model, also namely the homogenous network of distributed environment, all compute nodes must be configured with the same hardware and software hierarchies. And the tasks to be calculated are evenly assigned to each node. The computing efficiency and computational stability can be guaranteed to some extent. But if the computing time of each task is different even unknown, the corresponding computing performance of the whole system would be limited to a certain extent. And the costs of system expansion capability and the availability of compute nodes are very high as well. Furthermore, it is a fact that most existing computing resources are heterogeneous PCs with different hardware and software configuration on the Internet. Applying the even assignment strategy used in the PC cluster mentioned above to such heterogeneous distributed computing environment will lead to the waste of the available computing resource since the total computational efforts are determined by the compute node with the lowest computing performance. In this situation, how to utilize these heterogeneous computing resources efficiently to the maximum performance in implementing TTC evaluation with TS constraints is an important issue of great interest by power system engineers.

3.1 Design philosophy of the model of generalized compute nodes

As described above, the proposed intelligent grid computing architecture aims at exerting the computing power of each node to the most. A scheduling strategy with 'able person should do more work' feature is designed in this proposed model. The design sketch is given in Fig. 2.

This model comprises two kinds of nodes in a distributed Intranet/Internet network environment: (i) Computation manager: as the heart of the proposed computing model to implement the task pool creation, task monitor and task summary etc. (ii) Compute node: consisting of many heterogeneous distributed computing resources, e.g. the high performance server as well as personal computers (PC) as shown in Fig. 2, to implement the TTC evaluation with TS constraints corresponding to the requested tasks and return the temporary results to the computation manager. The Transient Security Assessment Tool (TSAT) [15] developed by Powertech Labs Inc. Canada is employed as the computing engine of each node, which ensures the architecture can handle AC-DC power systems with up to 100000 buses. The basic implementation procedures are described as follows.

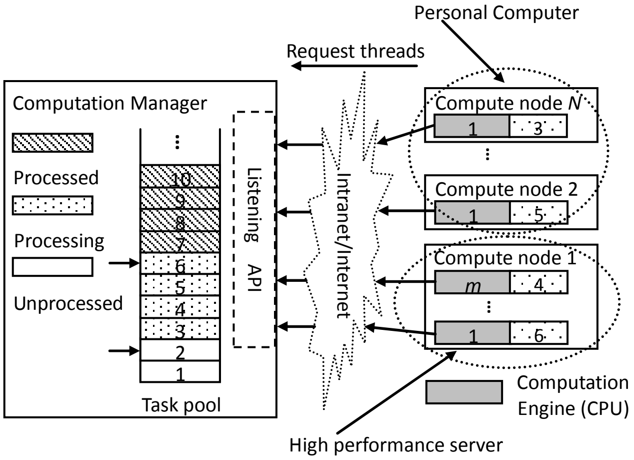

Fig. 2. Design sketch of the model of generalized compute nodes

(i) In light of the problem to be solved, the computation manager creates a task pool consisting of contingencies with different fault type. Then the computation manager opens the listening port to all available nodes;
(ii) These nodes create threads according to the number of logical processors (or logical CPUs) and send computation requests (or connections) to the computation manager;
(iii) The computation manager creates the corresponding working threads to respond (or connect) to these requests;
(iv) The computation manager assigns the tasks in the task pool to the working threads which have been connected to compute nodes;
(v) The assigned tasks are sent to the corresponding nodes by the working threads;
(vi) Once the calculation finished, the compute nodes return the results to the computation manager;
(vii) When detecting an idle node that have completed the assigned task, the computation manager send new task to it again through a working thread.

It can be seen that the number of tasks handled by the compute node is proportional to the performance of the node. In other words, a high-performance compute node can process more tasks comparing with a general PC. Matching the performance of the proposed intelligent grid computing architecture is the number of compute nodes that can do their best to fully exert the computing power of the whole system. In this way, the system loads can be dynamically balanced effectively as well.

A possible issue reducing performance should be considered elaborately. If a compute node is still handling an assigned task and other nodes are in idle state at the

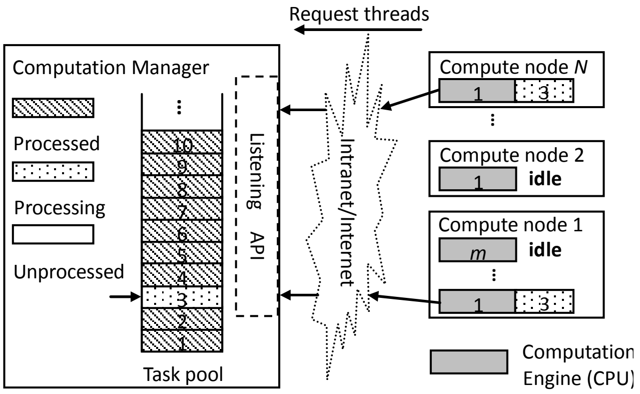

Fig. 3. Conditional resource preemption strategy

same time (no task can be assigned further in the task pool), a waste of the system computing resources will happen. In the paper, a strategy called conditional resource preemption is adopted to avoid timeout. Based on the strategy, when the situation mentioned above happened, one of the idle nodes will send request to the computation manager to handle the last unfinished task. Meanwhile, the node processing the same task doesn't know the task has been allocated to another compute node. Namely, two compute will handle the same task as shown in Fig. 3. The one finishing the task first will return the results to the computation manger and the other will discard the results of the unfinished task. Hence it is the strategy that makes the idle compute node reasonably and efficiently preempt the last handing task at the appropriate time.

3.2 Implementation of intelligent grid computing architecture

The logical system configuration of the designed intelligent grid computing architecture is given in Fig. 4. It consists of center manager, computation manager, compute node, client, web server and database. The center manager connects to the existing EMS/SCADA system or future control center in a smart grid for receiving the real load flow data. Furthermore, it is in charge of receiving 'Start' command from client to notify the computation manager to start the TTC calculation with TS constrains as well as receiving the results from the computation manager. The center manager and the computation manager interacting with each other can be regarded as a server which is the backbone of the intelligent grid computing architecture. The client provides dispatchers with easy access to monitor and manipulate operating status of the whole system. The web server allowing dispatchers to access conveniently involves results display, parameter management, user management and data management etc.

As described above, the implementation of computation manager is the key to implement the architecture. The multi-process and multi-thread technologies [18] are employed into the computation manager. Considering the function of the computation manager, it can be anatomized into multiple process objects. Every process object running independently is responsible for the specific function. Some processes would create multiple thread objects for the specified requirements. These thread objects can communicate with each other via several ways including global variables, signal and shared memory [18] etc.

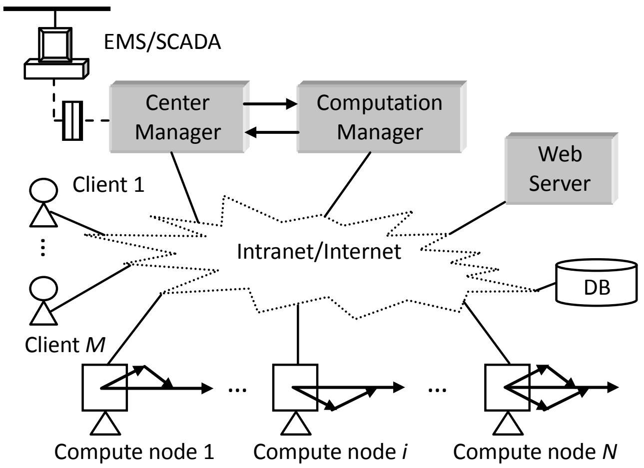

Fig. 4. Logical system configuration of the intelligent computing architecture

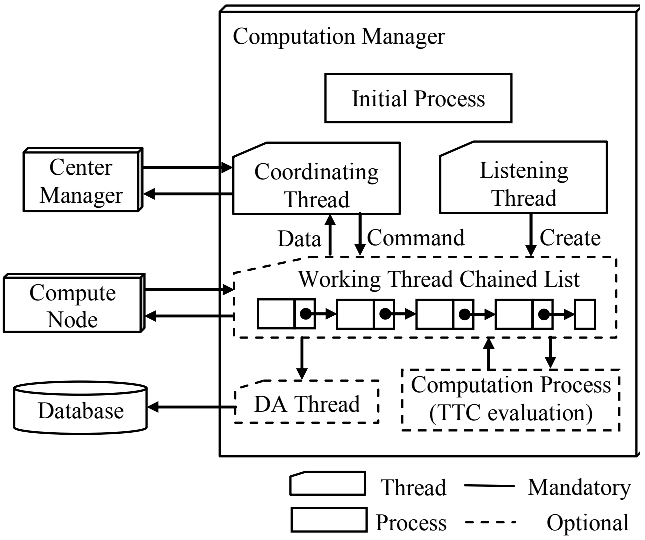

Fig. 5. Logical structure of computation manager

In Fig. 5, the logical structure of computation manager is comprised of the following components: initial process, coordinating thread, listening thread, database access thread, working thread chained list, computation process and so on.

The main function and features of each part in computation manager are described below.

(i) Initial process: is responsible for system initialization;

(ii) Coordinating thread: is the interface to the center

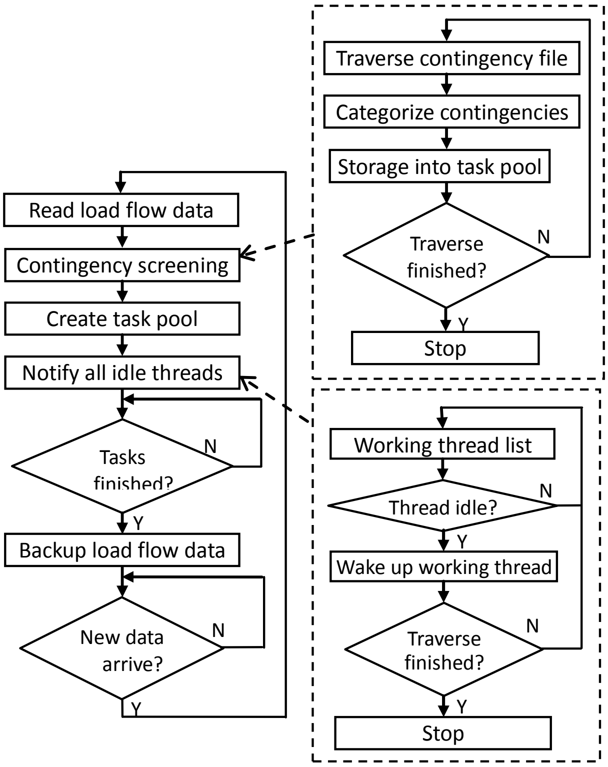

Fig. 6. Flow chart of coordinating thread module

manager and involves contingency screening, creation of task pool and the management of idle thread computation etc. The flow chart is shown in Fig. 6.

(iii) Listening thread: is responsible for the connection with compute nodes and creation of working thread etc.;

(iv) Working thread: is responsible for the communication with compute nodes, sending computing tasks and receiving calculation results etc.;

(v) Database access thread: is used for calculation results storage;

(vi) Computation process: is the optional calculating engine of the computation manager.

4. Robustness of the Intelligent Grid Computing Architecture

In order to keep the stability of the intelligent grid computing architecture running in a heterogeneous environment, the robustness of the system should be improved. The robustness mainly involves two aspects: dynamic scalability and fault-tolerance, which will discuss below and verify in Section 5.

4.1 Dynamic scalability

With the aim of fully utilizing idle resources distributed on the Internet anytime, the scalability must be considered. In general, the scalability is classified as static scalability and dynamic scalability. The notion of static scalability is defined as suspension and reconfiguration of the current running computing platform when the system needs to add or delete compute node. The whole system won't restart until this configuration finished. On the contrary, the dynamic scalability indicates that the computing system can adapt the addition and deletion of compute node automatically and implement self-management and self-maintenance of the system.

The proposed task level based intelligent grid computing architecture bears excellent dynamic scalability. When a compute node quits calculation abnormally, the computation manager would automatically assign the uncompleted task to another compute node. Accordingly, the results are not influenced by the abrupt change. Additionally, the computation would authenticate a new compute node and create a connection with it when the node wants to join the running system. In this case, the unprocessed task will be assigned to the new node. There is not any influence on the system as well. This in turn would increase the computing power through the new node.

In a nutshell, the proposed intelligent computing architecture has both excellent dynamic scalability and static scalability. The change of the number of compute nodes during working time would not result in interruption of the system.

4.2 Fault-tolerance

The TCP/IP and FTP based communication technologies are applied in the proposed architecture to guarantee the reliability of this proposed computing architecture. The retransmission mechanism of TCP/IP and FTP can ensure the massive data transfer reliability effectively.

A subtask level fault-tolerance mechanism is designed for the proposed computing architecture. The innate competitive advantage of this mechanism can simplify the fault-tolerance procedure and reduce the system overhead required by fault-tolerance. In view of the fault-tolerance mechanism, the computation is assumed as a relatively stable part while the compute node is considered as an unstable node (may join or quit the system anytime). So the designed fault-tolerance mechanism aims at the compute node. When an accident happens to a running node suddenly and it can't work anymore, the computation manager will be notified automatically and timely and reassign the uncompleted task to other compute node. In this way, the infinite waiting can be avoided efficiently.

Furthermore, in order to prevent the access violation from foreign system, the client side authentication mechanism is employed to make legal validity conducted by the computation manager for each compute node which wants to join the platform. Only authorized compute node can enter into this computing system.

5. Application Example

The hardware environment of the proposed platform is composed of 5 servers and 1 PC on a local intranet network. The corresponding simulation parameters of resources are given in Table 1. The center manager and computation manager run on the Server2, and others act as the compute nodes during the simulation.

Table 1. Computing Resource used in simulations

Parameter	Value	Logical CPUs
Ethernet	100 M	/
PC	Dell Optiplex 210L, Pentium4, 3.06G, 504MB, Windows XP Professional.	2
Server1	IBM xSeries 3610, Xeon(R), E3110, 3.20G Intel Dual Core, 4.00GB, Windows Server 2003	2
Server2	IBM xSeries 226, Xeon(TM), 3.20G Intel Quad Core, 2.00GB, Windows Server 2003	4
Server3	IBM xSeries 226, Xeon(TM), 3.20G Intel Quad Core, 2.00GB, Windows Server 2003	4
Server4	IBM xSeries 226, Xeon(TM), 3.20G Intel Quad Core, 2.00GB, Windows Server 2003	4
Server5	IBM xSeries 3610, Xeon(R), E5405, 2.00G Intel Octal Core, 8.00GB, Windows Server 2003	8

The following 3 schemes are designed to test the performance of the proposed computing archecture.

(i) Server 2 participates in the calculation with 4 request threads triggered;
(ii) 3 Servers (e.g. Server2+Server3+Server4) participate in the calculation with total 12 request threads triggered;
(iii) All computing resources shown in Table 1 participate in the calculation.

The step size of simulation is 0.01 second, and the simulation of each contingency lasts 5.0 seconds. Scheme (i) is related to the conventional sequential (or serial) algorithm. Scheme (ii) is related to the traditional and widely used well-known PC cluster based high performance computing algorithm (in a homogenous computing environment). Scheme (iii) is implemented via our proposed intelligent computing architecture. The corresponding calculation runs in a heterogeneous environment.

5.1 Performance testing of the proposed intelligent computing architecture

Fig. 7 shows the diagram of the IEEE New England 39-bus system. The test system is composed of 39 buses, 46 transmission lines, 10 generators, 19 loads and 4 areas. The transfer rule is defined as: load increase in area 4 whereas load decrease in area 2. Total 39 contingencies including 29 N-1 branch contingencies (i.e. single circuit outage) and 10 generator tripping contingencies are screened during analysis.

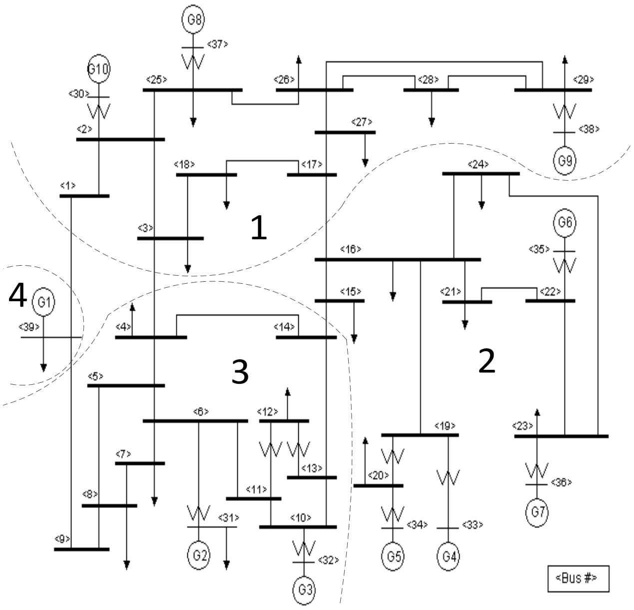

Fig. 7. The diagram of the IEEE New England 39-bus test system

First of all, to illustrate the reliability and stability of the designed grid computing architecture, total 10 trials were applied to the test system. The testing results are given in Fig. 8.

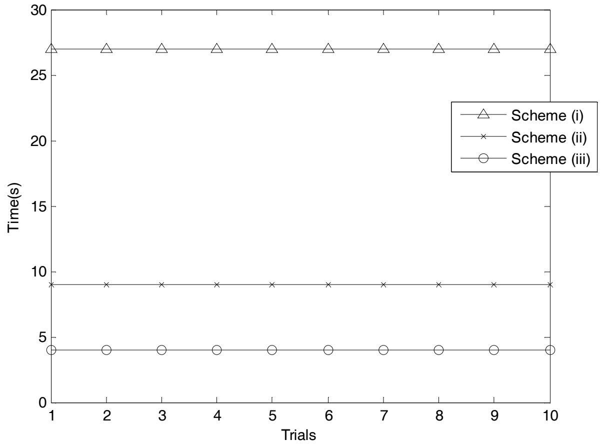

Fig. 8. Computing time over 10 trials

The average computing time and speedup ratio corresponding to each scheme described above are given in Table 2.

From Table 2, for Scheme (i), it took a long time to solve the problem. For Scheme (ii), according to the average computing time and the speedup ratio in Table 2, comparing with Scheme (i), it is obvious that the parallel algorithm is much better than the serial algorithm. For Scheme (iii), with joining of a dozen of logical processors, the performance of the newly formed heterogonous grid computing environment improves significantly. The whole computing time is remarkably reduced since these logical processors undertake a number of assigned tasks. Therefore, the proposed grid computing architecture can make full use of idle computing resources. Because of the high performance of Server5 with 8 logical CPUs in Scheme (iii), the speedup ratio of Scheme (iii) is much larger than that of Scheme (ii).

Table 2. Average computing time and speedup ratio of each scheme

Scheme	Logical CPUs	Average Computing Time (s)	Speedup Ratio
i	4	27.0	-
ii	12	9.0	3.00
iii	24	4.0	6.75

The assigned number of tasks of each compute node in Scheme (iii) over 10 trials is given in Fig. 9. The Servers (Server1, Server2, Server3, Server4, Server5) can handle more tasks than PC, because the computing performance of Servers is no doubt higher than that of PC. The results exactly reflect the 'able person should do more work' feature. The fluctuation of curve related to each compute node shows that the corresponding time of different contingency is different and unpredictable.

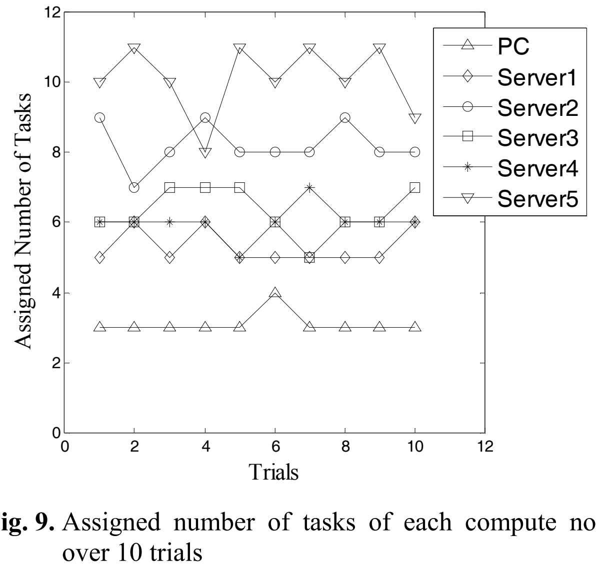

Fig. 9. Assigned number of tasks of each compute node over 10 trials

Next, in order to verify the robustness of the proposed grid computing architecture, the corresponding verification procedures are designed as follows.

(i) To test whether the system can automatically optimize the idle computing resources and run with high speed ratio without any user intervention when a new compute node joins the running system during simulation;

(ii) To test whether the normal operation of system would be interrupted by Intranet/Internet connection failure.

Two scenarios incorporating the Server1 (with 2 logical CPUs) and the Server2 (with 4 logical CPUs) are designed to implement the aforementioned test procedures.

Scenario 1:

For the Test (i), the Server1 firstly handles 20 contingencies, and then the Server2 joins at the second step so that two servers both handle the remaining 19 contingencies. The time to be taken at the second step is expected to be a third of the time taken at the first step based on the almost same frequency of each logical CPU and same processor architecture in the two compute nodes. The test is repeated three times to guarantee the accuracy and effectiveness of the test. If the average time is closed to the expected time mentioned above, it proves the validity of Test (i).

Scenario 2:

As for Test (ii), both two servers jointly undertake the 20 contingencies firstly, and then the Server2 is removed from the architecture. Only Server1 is responsible for the remaining 19 contingencies. Likewise, the time to be taken at the second step is expected to be triple over the time taken at the first step. Table 3 gives the test results.

Table 3. Results of Test (i) and Test(ii)

	Test (i)	Test (ii)
Actual time taken at the 1st Step (s)	25.0	9.0
Expected time taken at the 2nd Step (s)	8.3	27.0
Actual time taken at the 2nd Step (s)	9.0	27.3

From Table 3, it can be seen that the expected time and the actual time are almost identical. The conclusion can be drawn that Test (i) and Test (ii) demonstrate indirectly that the proposed grid computing architecture bears good robustness.

5.2 Engineering application

The proposed grid computing architecture is applied to the China-Jiangxi Power Grid to implement the online TS constrained TTC evaluation. One of high performance servers is connected to the existing EMS/SCADA system in the control center of Jiangxi Power Grid. The other computers serve as the computer nodes in the grid. The real time state estimation data from EMS/SCADA within each 5 minutes cycle, which consists of 554 buses, 728 transmission lines (transformer included), 32 generators, 604 loads and 2 areas in Jiangxi and central China. The transfer rule is defined as: total generation and load in area 2 and generation in area 1 increase simultaneously. Through a web based parameter management system, these parameters involving the number of critical contingencies, generator model, load model, transfer rule can be created and modified dynamically.

Total 292 contingencies including 211 N-1 branch contingencies (i.e. single circuit outage between 220kV and 500kV), 49 N-2 branch contingencies (i.e. double-circuit outage) and 32 generator tripping contingencies are employed to evaluate the TS constrained TTC. The actual computing time is less than 1 minute, which totally meets the requirement of online application for Jiangxi Power Grid. The average computing time and the speedup ratio corresponding to each scheme of China-Jiangxi Power Grid described above are given in Table 4.

Table 4. Average computing time and speedup ratio of each scheme of China-Jiangxi Power Gird

Scheme	Logical CPUs	Average Computing Time (s)	Speedup Ratio
i	4	194	-
ii	12	63	3.10
iii	24	30	6.47

It should be noted that it doesn't mean the more compute nodes, the better performance. The maximum number of logical processors is only allowed to be the number of tasks in the task pool. If extra compute nodes are added, it may lead to resources waste rather than high efficiency because of the bottleneck existing in the task level based system. If considering only the optimal number of logical processors ignoring the system cost, the proposed architecture is prone to perform best when the optimal number of logical processors is set to be equal to the number of contingencies. If the cost of system is considered, the optimal number of logical processors is determined by the acceptable processing time caused by the additional compute nodes. And the improvement of system performance should be simulated through different actual tests. After all, the processing time for each contingency varies with different initial power flow solution. The China-Jiangxi Power Grid system is tested with 6 compute nodes, a total of 24 logical processors less than a tenth of all the contingencies. Consequently, if the number of logical processors exceeds 200, the simulation can be sure to be completed in an impressively short time.

The final results are displayed in web mode. Fig. 10 and Fig. 11 shows the online results under normal operating condition with respect to a specific transfer rule. The web browser based result GUI is halved to present the TTC with respect to a certain critical contingency in Fig. 10 and the TS index with respect to the same contingency in Fig. 11. The 3D stacked column consists of two divisions: division 1 and division 2 as shown in Fig. 10. Division 1 shows the initial value of generation outputs of load demands while division 2 gives the value of TTC evaluation with TS constraints. The transient stability evaluation index in Fig. 11 means that under a certain contingency, the larger the value, the better the transient stability of the test power system. All these calculation results mentioned above are shown in online display mode, i.e. the results are refreshed automatically without any user intervention. In addition, the offline display mode to conduct simulation of historical events is also designed. Both online and offline display modes have the same appearance.

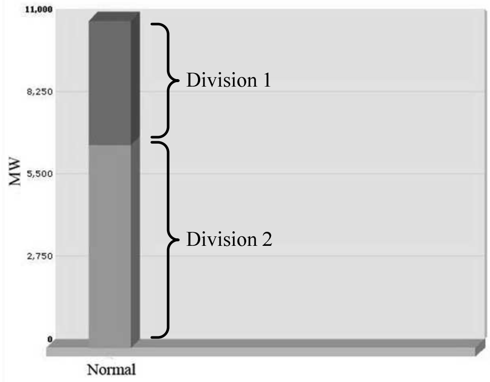

Fig. 10. Total transfer capability of China-Jiangxi Power Grid under normal operating condition

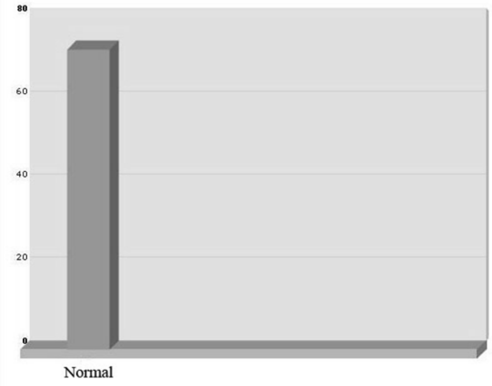

Fig. 11. Transient stability index of China-Jiangxi Power Grid under normal operating condition

Fig. 12 to Fig. 15 below show the TTC evaluation results under N-1 and N-2 contingencies in the web browser.

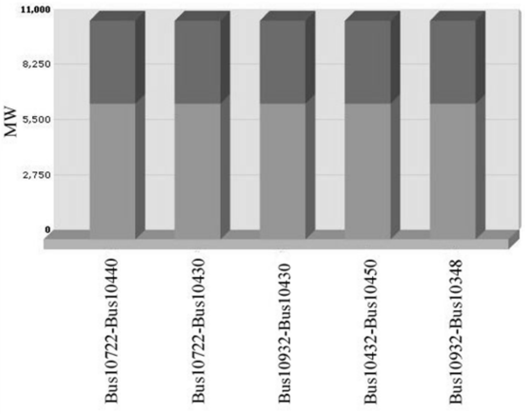

Fig. 12. Total transfer capability of China-Jiangxi Power Grid under N-1 Contingency

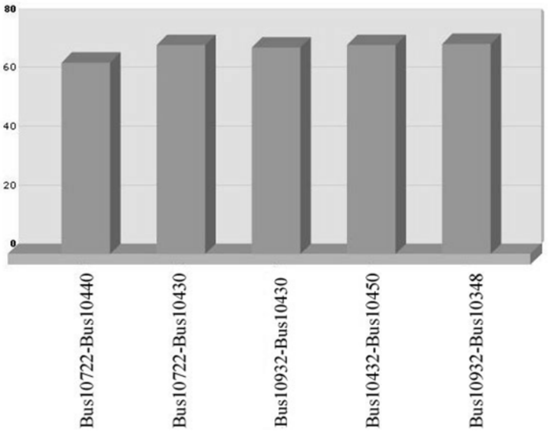

Fig. 13. Transient stability index of China-Jiangxi Power Grid under N-1 Contingency

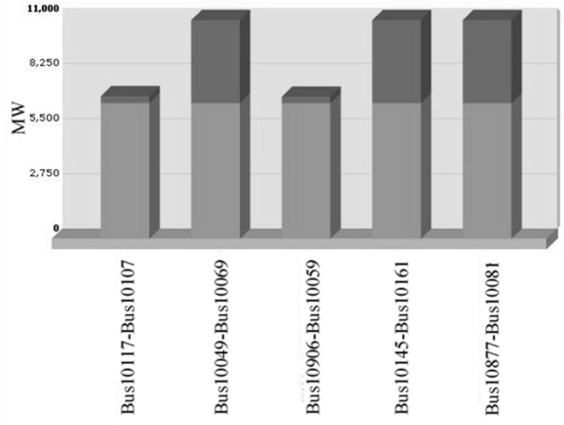

Fig. 14. Total transfer capability of China-Jiangxi Power Grid under N-2 Contingency

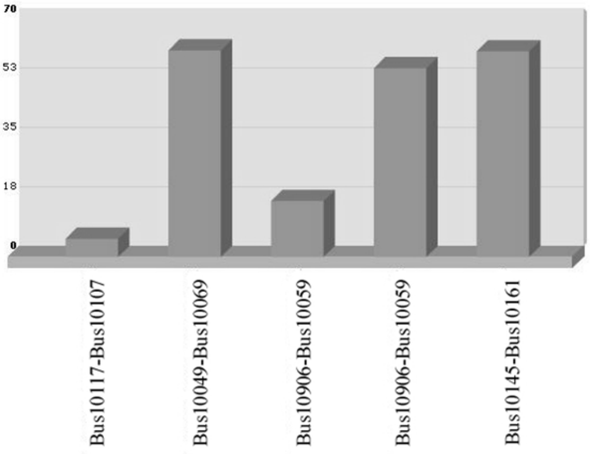

Fig. 15. Transient stability index of China-Jiangxi Power Grid under N-2 Contingency

Table 5 shows the TTC evaluation results of N-1 and N-2 contingencies.

Table 5. TTC evaluation results of N-1 and N-2 contingencies for China-Jiangxi Power Grid

Contingency Category	Branches	Transient Stability Index η	Total Transfer Capability (MW)
N-2	Bus10117-Bus10107	5.35	342
N-2	Bus10906-Bus10059	16.47	317
N-2	Bus10145-Bus10161	55.60	4138
N-2	Bus10877-Bus10081	60.55	4138
N-2	Bus10049-Bus10069	60.83	4138
N-1	Bus10722-Bus10440	65.04	4138
N-1	Bus10722-Bus10430	65.23	4138
N-1	Bus10932-Bus10430	65.38	4138
N-1	Bus10430-Bus10450	67.32	4138
N-1	Bus10932-Bus10348	68.12	4138

The generator relative angle within the simulation time of 5 seconds under the N-1 contingency Bus10932-Bus10348 given in the Table 5 is displayed in Fig. 16. The generator on the Bus10003 is set to be the Reference Generator. When three phase fault happens on line Bus10932-Bus10348, the generator relative angle between the generators on Bus10728 and Bus10771 reaches maximum. According to this value, the power angle based transient stability index calculated by the formula (1) is 68.12, i.e. the China-Jiangxi Power Grid is transient stable under this contingency.

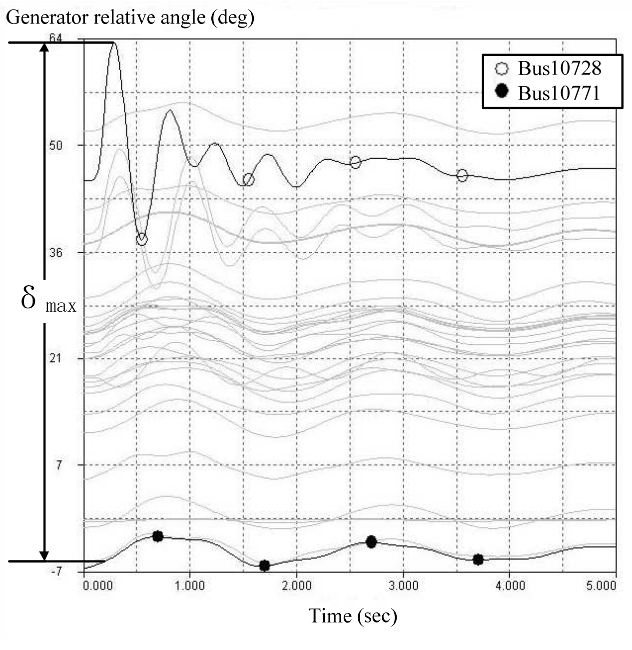

Fig. 16. Generator relative angle of China-Jiangxi Power Grid under N-1 contingency Bus10932-Bus10348

These preliminary results imply the potential application of the proposed intelligent grid computing architecture in the future smart grid era. However, to realize the system in the future control center (in a smart grid) even in the existing real control center, the possible challenges below will be involved.

(i) The corresponding data interfaces with external and third party systems. And the cybersecurity and integration issues need to be elaborately considered;

(ii) The possible potential impact on the existing operations of power systems. That means that proposed computing architecture should not have any negative impact on the existing operations.

(iii) The rapid and effective evaluation for the impact of high penetrations of renewable energy resources on smart grid. As one of the most important components in a smart grid, the renewable energy sources such as wind power and solar power are variable and intermittent and thus the evaluation tool should withstand the test of more strict, accurate and rapid requests.

6. Conclusion

Keeping interconnected power systems operating within security region and monitoring dynamic security margin constantly under normal operation conditions process a crucial significance of great interest by electrical engineers. In order to make extensive use of ubiquitous heterogeneous computing resources in Intranet/Internet, a task level based intelligent grid computing architecture for TS constrained TTC evaluation on the future smart grid is proposed in this paper. The architecture can wrap all the idle resources into integrity to fully release the high performance of computers. The design philosophy and implementation of the proposed grid computing architecture are discussed in detail. Furthermore, the robustness of the proposed distributed parallel computing architecture is analyzed as well. Case studies on the IEEE New England 39-bus system and a real-sized Chinese power system are carried out to illustrate the effectiveness and validity of the architecture. With the support of grid computing technology, the architecture to some extent provides a possible and potential solution of computing-intensive applications of the future smart grid.

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