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정태 안전성 평가를 고려한 무효전력 전압제어를 위한 A-team기반 접근법

A-team Based Approach for Reactive Power/Voltage Control Considering Steady State Security Assessment

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ABSTRACT

In this paper, an A-team(Asynchronous Team) based approach for Reactive power and volage control considering static security assessment in a power system with infrastructural deficiencies is proposed. Reactive power and voltage control problem is the one of optimally establishing voltage level given several constraints such as reactive generation, voltage magnitude, line flow, and other switchable reactive power sources. It can be formulated as a mixed-integer linear programming(MILP) problem without deteriorating of solution accuracy to a certain extent. The security assessment is to estimate the relative robustness of the system in its present state through the evaluation of data provided by security monitoring. Deterministic approach based on AC load flow calculations is adopted to assess the system security, especially voltage security. A security metric, as a standard of measurement for power system security, producting a set of discrete values rather than binary values, is employed. In order to analyze the above two problems, reactive power/voltage control problem and static security assessment problem, in an integrated fashion for real-time operations, a new organizational structure, called an A-team, is adopted. An A-team is an organization for agents which are all autonomous, work in parallel and communicate asynchronously, which is well-suited to the development of computer-based, multi-agent systems for operations. This A-team based approach, although it is still in the beginning stage, also has potential for handling other difficult power system problems.

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국문초록

본 연구에서는 하부구조적 결함을 갖는 전력계통의 정태 안전성 평가를 고려한 무효전력 제어 문제를 해결하기 위하여 A-team(Asynchronous team) 이론을 이용한 접근법을 제시한다. QVC는 무효전력 발전량, 전압치, 선로조류 및 다른 무효전력장치에 대한 제약조건하에서 최적의 전압을 유지하는 문제로써, 해의 정확도를 크게 해치지 않는 범위내에서 혼합정수계획법(MILP) 문제로 수식화하였다. 안전성 평가는 계통의 모니터링을 통하여 얻어진 현재의 자료를 평가하여 상대적 강인성을 추정하는 것으로 교류 전력조류법에 기반을 둔 결정론적인 방법에 의해 계통안전성, 특히 전압안전성을 평가하였으며, 이진치 대신에 다수의 이산치를 제공하는 안전성 계량을 사용하였다. 계통의 효율적 운전을 목적으로 위의 두 문제를 통합하여 풀 수 있도록 A-team으로 명명된 새로운 조직기법을 도입하였다. A-team은 자치적(autonomous)이고, 병렬적으로(in parallel) 동작하고, 비동기적으로(asynchronously) 정보교환을 하는 agent들을 위한 일종의 조직법으로 다수의 프로그램(computer-based multi agent)을 이용한 운용시스템의 구성에 적합한 방법으로 알려져 있다. 이 A-team을 이용한 방법은 실계통에 적용하기 위한 초기단계에 머무르고 있으나 대형계통의 여러 복잡한 문제를 해결할 수 있는 가능성을 갖고 있다.

1. INTRODUCTION

Power system operations require a significant amount of man power and resources to supply the consumers such as homes, businesses and industries with reliable, high-quality electrical energy at a reasonable cost. These operations are highly unstructured, nonlinear, stochastic and time-varying. That is, recent environmental concerns, the uncertainty of world fuel supplies and the high cost of power plant construction have altered the way in which the existing power system is operated. Over past decade, the power systems in all over the world have experienced system instabilities with increasing frequency when they operate more closely to the limits for which they were designed. Prominent power system engineers remarked that most major blackouts during the past decade have been caused by reactive power voltage control problem[1]. The goals of this control(QVC) can be regarded as an attempt to achieve an overall improvement of system security, service quality and economy. System security requires an adequate voltage levels and reactive power reserves in order to maintain voltage stability as critical contingencies occur. The service quality and economy require an appropriate voltage control at all system buses and *consumer terminals within tolerable limits,* in order to insure proper reactive power line flows which result in minimal transmission losses, operating costs and other objectives. Thus, a paramount objective in power system operation is developing methods to assess the security of the existing system, based on voltage problem. The requirement among these methods is the development of on-line analysis techniques. Since the power system infrastructure covers large physical areas, there are lots of the changes and the number of unexpected disturbances that can occur to the system. To assess security of power system in a integrated fashion with voltage problem requires to consider several constraints such as equality constraints for serving existing consumers, inequality constraint for network operation under normal or abnormal conditions and environmental constraints limiting emissions. Existing techniques are not adequate for modeling the problem that considers all these factors in an integrated formulation[2,3]. Even if all the above modeling difficulties were to be overcome, it is not easy to solve the overall problem on-line with traditional algorithms and computational techniques. In order to obtain optimally on-line solution of this problem, new computational techniques like parallel processing, object-oriented porgramming can be employed. This paper proposes an A-team, a new organizational structure suggested by S.N.Talukdar[4~7], for solving the integrated problem in parallel. A-team is an organization with agents which are autonomous, among which iteration and feedback are allowed, and which cooperate asynchronously. The agents encapsulate traditional optimization algorithm as well as numerical softwares needed to analyze the problem. All the agents communicate asynchronously, meaning that they can work in parallel without ever interrupting or delaying one another. Several researches using this A-team theory have already reported to solve complicated power system problems[8,9]. The results of the researches demonstrated that the algorithm using A-team is compared favorably with conventional ones.

2. QVC PROBLEM

2.1 Concept and Control of Reactive Power

The concept of reactive power[10], by convention symbolized as Q, is much more elusive than that of real power, P. The integrated value of P over one or more cycles is a positive quantity representing energy, but the corresponding integrated value of Q is zero. P unambiguously represents the flow of energy converted into electrical form at a plant and dissipated or reconverted into heat, light or other form elsewhere by the system's connected load. Q represents energy in continuous interchange between dynamic magnetic(inductive) and electric (capacitive) fields. Since Q averages zero over each cycle, potential disparities between the two forms are accommodated by fluctuations in bus voltage or line voltage drops; hence the tight coupling between reactive power and system voltages. During being characterized by operation at relatively low voltage levels, voltage profiles were maintained easily by proper distribution of shunt capacitors about the system. However, with the introduction of higher voltage levels and fields producing large amounts of reactive power, the problem of maintaining the reactive power balance needed to insure an acceptable voltage profile has become increasingly severe. Primary available means controlling the production and/or absorption of reactive power(VARs) including generator exciters, transformer tap changers and switchable shunt capacitors/reactors. In addition, several types of switched thyristor advanced control devices are being introduced into the power system. These devices have become to be known as FACTS(Flexible AC Transmission System), and encompass static VAR compensators(VARs), consist of a thyristor controlled reactor in series with a fixed capacitor, and static condenser(STACON), based on a voltage sourced converter. Both devices control bus voltage through injecting a reactive current at the bus. Present operating procedure is to monitor and control a number of buses in the system on the basis of operator experience, operating practices and load flows.

2.2 Problem Statement

In general, optimal reactive power and voltage control can be expressed as a nonlinear optimization. Let X denote the vector of "state" variables and U the vector of "control" variables which are composed of bus voltage and transformer tap ratio. Then the equality constraints of the problem can be expressed as

$$g(X, U)=0.$$

which represents real and reactive power supply and demand balance. The inequality constraint applied to state, control and output variables also can be expressed as

$$h(X, U)\leq 0.$$

These are classified into generation constraints, voltage limit constraints, security constraints on line flows, capacity limit for reactive power compensation sources and environmental constraints limiting emissions. The objective functions, $f(X, U)$, in the problem such as economic criterion, pollution criterion and combined economic/security criterion can be applied. However, modeling some constraints and objectives is complicated by the regulatory uncertainties and the information inadequacies. Consequently, the consideration of these constraints and objectives is optional to avoid unnecessary restrictions that increase the computation time and deteriorate the computational efficiency.

2.3 QVC Formulation

One of the main objectives operating the power system is to supply the consumers the electrical energy without even short period of failure at a minimum cost. The problem of QVC can be formulated as :

$$
\begin{aligned}
(\mathrm{QVC}):\ & \mathrm{Min}\ f(X, U) \\
\mathrm{s.t.}\ & g(X, U)=0 \\
& h(X, U)\le 0
\end{aligned}
$$

The control vector consists of continuous variables and discrete variables, so that the problem should be formulated as a mixed-integer programming fashion. The original problem of QVC is in the form of nonlinear programming. However, the mathematical expression of this problem is presented here as a linear programming problem to improve computational efficiency and to obtain modeling easiness. Now, the problem of QVC formulated as a linearized form suitable for a mixed-integer linear programming is as follows[11] :

$$
\begin{aligned}
(\mathrm{QVC}):\ & \mathrm{Min}\ C_1X+C_2U \\
\mathrm{s.t.}\ & AX+BU=w \\
& DX+EU\le z
\end{aligned}
$$

3. SECURITY ASSESSMENT

3.1 Security Assessment Approaches

There are currently two basic approaches to the estimation of future system security namely the deterministic approach and probabilistic approach. The deterministic technique requires that certain calculations such as AC loadflow be made for all conceivable future contingencies. The results of these studies are then reviewed and a judgment is made of whether or not some corrective action is required to maintain adequate system security. The probabilistic approach uses the probability of all the constituent components comprising the power system, in which the unplanned behavior of each component must be quantified normally by means of associated probabilities of occurrence of certain conditions. The probabilistic approach can supply a consitent criterion for control action given the results of the contingency tests in comparing to the deterministic one which does not take direct account of the unequal probability of occurrence of each system contingency. However, the deterministic approach clearly indicates those operating conditions that would result in a breach of system security. The first stage in the assessment of security is the development of a set of events whose occurrence would be considered to be a breach of security. These events might typically include :

(a) voltage violation at any bus
(b) overload of any transmission line or other equipment
(c) insufficient real and/or reactive power generating capacity

3.2 Security States and Assessment Process

Power system conditions are described by several operation states, which are governed by three sets of generic equations-one differential and two algebraic. The differential set encodes the physical laws governing the dynamic behavior of the system's components. The two algebraic sets comprise equality constraints which equate the system's total load and total generation balance and inequality constraints which state that some system variable as currents and voltages must not exceed maximum levels representing the limitations of physical equipment. A basic framework for measuring security based largely on operating limits was defined in 1967 by Dy Liacco[12]. He described a security regime divided into Normal, Alert, Emergency and Restorative states. In addition to the four states discussed above, In Extremis state was proposed by Fink and Carlsen[13]. This is the most common form of security metric which produces a set of discrete values. Discrete metrics provide better resolution of power system security than binary ones since most sets of discrete values have on secure value and several different insecure values. The relationship among the five states can be shown in[1,13].

The power system is operating in the Normal state when all operating limits are satisfied and load and generation are balanced. In this state, reserve margins are sufficient to provide an adequate level of security with respect to the stresses to which the system may be subjected. If the security level falls below some threshold of adequacy, and if the probability of disturbance increases, then the system goes into the Alert state. In this state, the power system is still operating within all limits, but a reasonable contingency could cause it to violate some inequality constraints; e.g., line thermal limits or bus voltage magnitude limits. The Emergency state is entered when any operting limit in the power system is violated, so that action is taken to return the system to at least the Alert state. If these measures are not taken in time, or are ineffective, and if the initiating disturbance or a subsequent one is severe enough to overstress the system, the system starts to disintegrate and enters In Extremis state. In this state, equality as well as inequality constraints have been violated and emergency control action should be directed toward salvaging as many portions of the system as possible from total collapse. The Restorative state exists when some remaining equipment still operating within rated capability and some load is not supplied, and action is begin taken to restore power to the all lost loads and reconnect the system. The objective of the general security assessment process is to determine the security state of the power system ofr some given initial condition. Transitions to the Emergency and Restorative states are easily detected and the Emergency or Restorative states can be determined without any difficulty from the initial conditions. The difference between the Normal and Alert states is much more difficult to detect. A contingency occurring while operating in the Alert state can possibly lead, through the Emergency state, to a blackout. For this reason, within this framework of security states, the major problem in security assessment has been to determine whether a system is operating in the Alert state. There are four major steps in the security assessment process. Of course, the method used to perform each step may differ from approach to approach, and from utility to utility, but the general outline of the process remains the same :

(a) Select a base case operating state, and prepare data describing it.
(b) Select contingencies, unplanned outages of one or more power system elements, such as transmission lines, transformers or generators.
(c) Evaluate contingencies, simulating the effect of each contingency on the base case.
(d) Interpret the simulation results, and report conclusions.

3.3 Contingency

Because security is related to the ability to continue operation after a contingency occurs, an ideal assessment would consider the effects of every possible contingency. But the number of possible contingencies in a typical power system is very large, and also the probability of a contingency occurring goes down as the number of components in the contingency goes up. Therefore, the number of contingencies to be analyzed is limited by one of several methods, making a list of contingencies to analyze by contingency selection algorithm. The effect of a contingency on a power system can be divided into transient and steady state effect. When an unexpected outage of equipment such as generators or transmission lines occurs on a power system, large transients may occur during the next few voltage cycles. Both transient effects and steady state effects can cause additional equipment outages. The ability of the power system to withstand the transients is called dynamic security. The ability of the power system to continue operation after the transients have died out is steady state security. For steady state security, the numerical algorithms are commonly referred to as load flows. Full AC load flow method evaluates the voltage solution for the power system with contingency. The calculation results are the complex voltages at every bus of the power system, the corresponding transmission line real and reactive power flows, generator and load complex power values and transformer tap positions. DC load flow method assumes constant voltage magnitudes and reactive power flows, and evaluates only the real power flows on the network. For dynamic security, as contingency evaluation methods are integration method and direct energy method. The computational burden of the former is prohibitive for on-line assessment. The latter is being used experimentally, but are not widespread. In this paper, steady state security assessment based on full AC load flow method is focused.

3.4 Techniques for Voltage Security

The secure operation of the power system involves first assessing security, and then taking action to maintain security at an adequate level. Some typical questions relevant to voltage security assessment are as follows[14,15];

(a) What are the security criteria to which the utility operates?
(b) How are bus voltage limits set? What is the basis for setting them?
(c) What corrective actions are taken to correct or prevent low voltages?
(d) When no voltages are in violation, what voltages do the operators like to look at, and why?

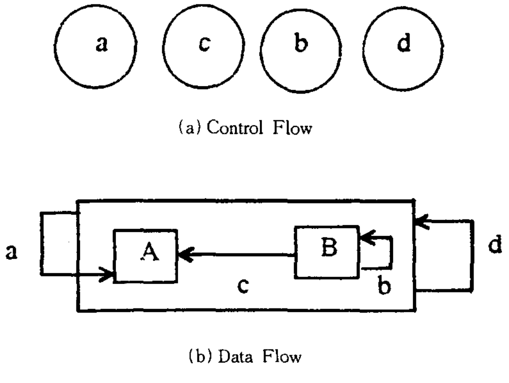
A formal method of comparing of voltage problems is not yet well-developed. In general, the problems at lower voltage levels are local in nature, while the problems at higher voltage levels can spread through and beyond the power system or are more likely to lead to voltage collapse. Most operators seem uncertain of what voltages to maintain and how to go about maintaining them. They know that the security implications are serious, and are aware of the mechanism of voltage collapse, but they don't have any analytical tools to predict this event reliably, although some mentioned divergence of loadflow as an indicator. When discussing security, power system opertors speak casually about whether the power system is secure, or insecure. But they also discuss how secure the system is. This is often done in terms of an amount of security, or the distance from insecurity. This suggests that some form of distance value would be an acceptable measure of security. For voltage security assessment, the sum of absolute value of differences between bus voltage and voltage limit over all buses with violations, or $\sum_{i=1}^{M} W_i \cdot |V_{bus} - V_{limit}|$ where M is total number of buses with violations and W_i is weighting value with respect to the importance of the violated bus, can be used as a distance measure. More complex numerical measures, of course, are possible. The security status of power system can be discussed and classified by these distance measures. To alleviate voltage problems can be employed corrective actions such as shunt switching, tap changing, generator MVAR changing, load switching, off-line generator starting and load shedding.

4. DESIGNING A-TEAM

4.1 Definition of A-team

The net capability of a work force to perform tasks depends not only on the inherent capabilities of its agents, but also on how they cooperate. In other words, net capability is invariable different from the sum of the inherent capabilities, and is sensitive to the organization used. There are two broad classes of organizations : hierarchy and non-hierarchy called a hetrarchy. The problem of designing an organization involves a choice between a hierarchy and a hetrarchy, the former having the disadvantages of supervisory overhead and fragility, the latter, of inefficiency and strangeness. The

A-team resulted from the desire to develop a computational framework for the systematic design of organizations that combine both human and computer-based agents. An Asynchronous team (A-team), designing a decentralized organizational scheme, is defined by Talukdar[4~7] as any super-agent, an aggregation of lesser agents, whose agents are autonomous, whose communications are asynchronous and whose data flow is cyclic. Based on the assumption that all communications among a finite set of agents can be modeled by a finite set of shared memories, A-team(a set of super-agent) can be modeled as a network of memories and agents. It is convenient to represent this network by a directed graph, called a data flow, whose nodes denote memories and whose arcs denote agents. Each agent reads data from the memory at its tail, processes these data, and writes the results into the memory at its head. That is, the data flow visualizes the routes by which the data exchanges among agents may occur. Also, supervisory relationships among agents is denoted by another directed graph, called a control flow, whose nodes represent agents and whose arcs represents the supervisory relations among them. Fig. 1 represents the control flow and data flow of an A-team. The two rectangular boxes labeled 'A' and 'B' are memories. The agents are the arrows labeled 'a', 'b', 'c', 'd' in the data flow, and circles in the control flow[9].



(a) Control Flow

(b) Data Flow

Fig. 1 Control flow and data flow of A-team

4.2 Characteristics of A-team

The most important features that characterize A-teams are summarized as follows[7].

(a) Autonomous Agents : Agents with a multitude of skills are combined so they complement and help one other. And they make their own choice about their data processing policy for input selection, scheduling, etc.

(b) Asynchronous Communication : Most agents use available information in shared memories without any synchronization among them. This renders the agents to read and write information without waiting for results from another and enables a highly parallel implementation.

(c) Open Organization : Since autonomous agents are completely independent of any other agent, new agents can be added or current agents deleted without notification for the remaining agents.

(d) Cyclic Data Flow : Agents retrieve, modify and store information continuously in the shared memories. A continuous flow of modifications is carried out by the agents, such that the iteration and feedback among them are possible. As a result, the agents develop and maintain better solutions to the problem.

4.3 Agents in A-team

Like rules in an expert system, the number of agents in an A-team tends to grow continually. In order to form each algorithm into an autonomous agent, the algorithm must be able to choose when to work and what solution to work on, and be able to deposit its output into a shared memory. These functionalities can be easily be appended to the beginning and/or the end of nearly any algorithm. The major agents involved in solving the QVC and security assessment problem are :

- Data Acquisitioner(DA) : to collect the latest data of power system and solutions.
- Random Initializer(RI) : to provide starting points for the A-Teams.

- Contingency Generator(CG) : to generate contingencies and to analyze them.
- Loadflow Calculator(LC) : to calculate the power flow of the system in order to obtain the system state.
- Creator(CT) : to generate the optimal solution in each situation using mixed-integer linear programming.
- Security Assessor(SA) : to assess the system security in terms of framework based on Fink and Carlsen.
- Results Reporter(RR) : to report the results to the user.
- Destroyer(DT) : to eliminate the obsolete solutions by employing the policy that selects a solution in solution memory with linear probability distribution, which has probability zero of selecting the best solution in memory and increases linearly until the worst solution.

4.4 Working Strategy

To visualize how the A-team suggested here works, think of the structure of A-team as a distributed collection of two memories in Fig. 2. One of these memories contains the data of power system being considered and populations of coarse (initial) solutions to the problem created by random initializer agent. The other contains population of improved solutions generated by creator agent based on mixed-integer programming. Before all the agents of an A-team start running, it is necessary to initialize the coarse solution memory in Fig. 2 with some number of solutions. The coarse solution memory is initialized and modified continually by random initializer algorithm which creates a random feasible solution of the problem. Each population is continually transformed by agents working in parallel. One agent, called creator, add members to the population, other called, destroyer, cull members from it. The creator works to produce solutions that are better in terms of its criterion; destroyer tests solutions with respect to its criterion and eliminates those that fail.

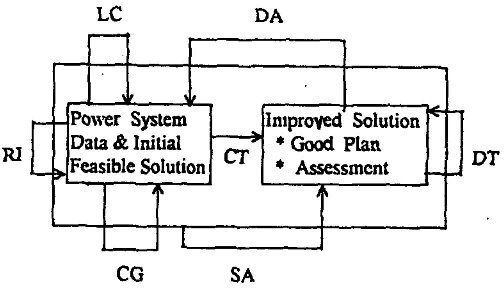


Fig. 2 The structure of an A-team for QVC/Security

The A-team described in this paper can be implemented using a server/client structure. Agents are clients that request information through remote procedure calls to process to the shared memories that are servers. Servers reply client's requests in a first-in-first-out fashion, which serialize requests, therefore avoiding simultaneous accesses of different clients(agents) to common data in a same shared memory. Because an A-Team has autonomous agents sharing common memories, and servers and clients are individual processes, it can be implemented in one or more computers. In this paper, the results of A-Team using only one computer is presented.

5. RESULTS

The A-team developed in previous sections has been applied to the small power system, IEEE 14 bus system in order to demonstrate its effeciency and availability. The system consists of with 14 buses, 20 lines 5 generators, 3 tap-changing transformers and 3 capacitor banks(bus 4, 10, 14). Some results from tests on the system with line 4 outage are shown in Table 1. The lowest bus voltage is 0.914, per unit value, and 9 buses(about 70% of total buses) have a low voltage problem as lower limits are 0.95. The curves in Fig. 3 display, respectively, the changes in operating cost for two systems, base case system and line 12, 17 outaged system. Operating cost was approximated by a weighted sum of real power generations[16].

6. CONCLUSIONS

This paper has outlined a process for solving reactive power/voltage control and security assessment problem in a power system. The reactive power/voltage control problem is formulated using a mixed-integer linear programming code, and system security is assessed by a deterministic approach based on AC load flow calculations. The integrated problem is solved by an asynchronous team of agents, an organization for agents which are all autonomous, work in parallel and communicate asynchronously. The results are not bad as compared to the results produced by conventional iterated methods[16]. But, it is reasonable to expect that the A-team approach can get far better solutions in a shorter time, provided that good agents, such as Random Initializer in this study, are given. The A-team is open(so new agents can be easily added), distributable(so it can be readily implemented in a network of computers), and effective(so it can find good solutions). The solution process has, as yet, only been tested on small and relatively uncomplicated problems(IEEE 14 bus system); parctical issues of problem formulation

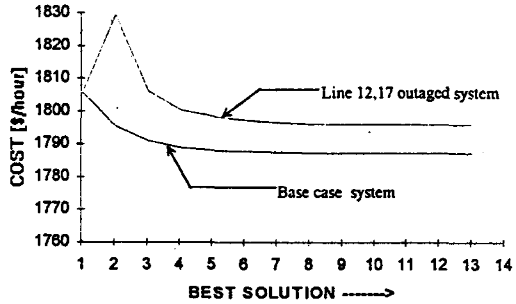


Fig. 3 Evolution of the Operating Cost

Table 1 Results for line 4 outaged system

vari	initial value	5 best solution values in solution memory				
V1	1.000/ 0.000	1.049	1.049	1.048	1.046	1.049
V2	0.962/ -8.674	1.023	1.023	1.022	1.019	1.023
V3	0.940/-18.212	1.004	1.005	1.002	0.996	1.003
V4	0.916/-18.733	0.989	0.989	0.987	0.984	0.988
V5	0.914/-18.557	0.988	0.988	0.987	0.984	0.988
V6	0.962/-27.130	1.030	1.030	1.032	1.021	1.030
V7	0.956/-22.308	1.020	1.020	1.027	1.024	1.021
V8	1.000/-19.138	1.042	1.042	1.049	1.051	1.042
V9	0.941/-26.292	1.021	1.021	1.025	1.018	1.021
V10	0.927/-28.166	1.013	1.013	1.017	1.008	1.013
V11	0.931/-29.077	1.009	1.009	1.012	1.002	1.009
V12	0.924/-29.955	0.997	0.997	0.999	0.988	0.997
V13	0.936/-28.664	1.009	1.009	1.012	1.001	1.009
V14	0.918/-28.587	1.004	1.004	1.008	0.998	1.005
Q1	0.976	0.000	0.000	0.000	0.000	0.000
Q2	50.000	50.345	50.328	50.595	50.916	50.410
Q3	40.000	36.280	36.354	35.352	31.958	35.569
Q4	0.000	4.947	4.952	4.875	4.743	4.936
Q6	49.998	50.644	50.586	51.313	51.056	50.980
Q8	25.897	13.425	13.339	13.452	16.957	13.704
Q10	0.000	9.820	9.829	9.630	9.251	9.778
Q14	0.000	4.873	4.879	4.748	4.541	4.844
T1	1.000	1.0250	1.0250	1.0250	1.0375	1.0250
T2	0.975	0.9875	0.9875	0.9750	0.9750	0.9875
T3	0.9625	0.9375	0.9375	0.9375	0.9500	0.9375
COST	1914.961	1879.0874	1879.0687	1879.3730	1880.6621	1879.1937

have not been taken into account. Many implementation questions must be answered before the process can be applied to real large-scaled power systems and real-time operations.

7. ACKNOWLEDGEMENTS

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