A MCDM Knowledge Based Scheme for Coordinated Voltage Control

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***Abstract*—A new real time power voltage control strategy is proposed in the paper. A novel off-line evolutionary multi-objective optimization algorithm called jumping genes is used to generate the wide spread control solutions which are readily stored into a knowledge data base. A separate on-line multiple criteria decision making scheme is established for selecting the appropriate control solution. This concept of power voltage control has been demonstrated by a representative 6-buses nonlinear power system model. The system output performance is speedy and accurate.**

***Index Terms* — voltage stability, voltage control, genetic algorithms, multiple criteria decision making**

I. INTRODUCTION

With the advent of open generation markets and the use of transmission systems beyond their planned basis, to solve a voltage stability problem of a power system is of a common interest to the power control community.

The coordinated arrangement and switching voltage control devices are the obvious and promising approaches to cope with the voltage instability problems. The successfully noticeable applications of the coordinated voltage control (CVC) are already existed in France and Italian [1-3]. The concept of CVC for a modern power system is a large-scale, highly constrained nonlinear combinatorial optimization problem. It is difficult for the traditional optimal methods to obtain a satisfactory result.

The tree search method and modern heuristic optimal methods are reported for global search of voltage optimal control. [4-6] However, these techniques suffered from low convergence rate when the system scale increases.

Considering the prospect of interconnection between systems and increasing power system scale, it is not proper just to consider the voltage optimal control as a single but pre-dominant objective problem any longer. There are also economic, operational and even environmental factors to be under consideration.

As mentioned above, voltage instability control is considered to be a multi-objective optimization problem. The available control solutions are numerous and each control solution is unique. Due to various operation requirements of the power system, the required solutions to cover the vastly diversified system behaviors must therefore be quite well spread or even into the extreme conditions.

A newly developed jumping genes evolutionary algorithm (JGEA) [7] is used in this paper to search multi-objective solutions of CVC. Rather than the usual deficiency of diversified EA schemes, this new scheme can produce a set of comprehensive non-dominated Pareto-optimal solutions which are widely spread along the Pareto solutions front.

Although these obtained solutions may only be off-line created, a method to store these valuable results into a data bank for on-line control is therefore proposed. The on-line selection scheme is based on the technique of Multiple Criteria Decision Making (MCDM) [8][9]. The combination of JGEA and MCDM can then form an intelligent knowledge data banking system for on-line control of the power systems.

The organization of this paper is as follows: Section II provides the basic information and structure of the knowledge based MCDM voltage control system. This included the theoretical background of the coordinated voltage control system, the off-line searching scheme and on-line selection method. The demonstrative simulated results of a six-buses power system are given in Section III. The necessary concluding remarks are stated in Section IV.

II. A KNOWLEDGE BASED MCDM SYSTEM

The overall optimization and control schemes of this paper can be summarized by the block diagram as indicated in Fig.1. It comprises of the routes for off-line optimization by testing various typical faults to the power system. The obtained results through the JGEA optimization scheme are stored into the Knowledge Data Base (KDB) which can readily be used for selection via MCDM scheme for real time control.

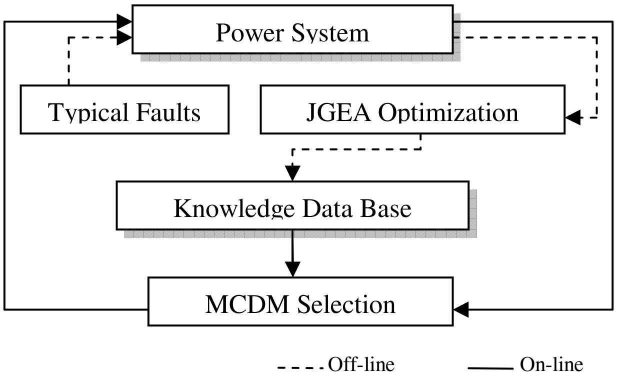

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Fig.1 Knowledge based MCDM control

A. *Coordinated voltage control*

The principle of CVC is to utilizing the local information to activate the necessary device and at the same time to coordinating the availability of power resources from other areas. CVC relies upon the simulated performance of a power system in accordance to the predefined system model that governs the devices connection, control device's statues, and current states of the power system. On the basis of performance, a series of control strategies can be determined for enhancing the overall control of the power system.

The required power system model of interest can be mathematically expressed in the hybrid differential-algebraic (DA) form [4]:

$$\frac{dx}{dt} = f(t, x, w, z(k)) \qquad (1)$$

$$0 = g(x, w, z(k)) \qquad (2)$$

Where x is the dynamic state variable and w is the algebraic state variables that can change instantaneously due to changes in x and $z(k)$. $z(k)$ denotes discrete control variables that can change only at the fixed time instant given at a selected sample time.

The involved control devices such as capacitors, load tap changers as well as the load shedding can be modeled as the discrete control variables. The activation of these devices is a fixed step action and the use of the load shedding action should be the last effort for the voltage recovery. This aggregate exponential recover load modeled [10] may apply for the load shedding models as follows:

$$dx_{i,p} / dt = -\frac{1}{T_{i,p}} x_{i,p} + P_{i,0}(V_i^{\alpha_s} - V_i^{\alpha_t}) \qquad (3)$$

$$P_{di} = (1 - n_{di} D_{shed})\left(\frac{x_{i,p}}{T_{i,p}} + P_{i,0} V_i^{\alpha_t}\right) \qquad (4)$$

$$dx_{i,q} / dt = -\frac{1}{T_{i,q}} x_{i,q} + Q_{i,0}(V_i^{\beta_s} - V_i^{\beta_t}) \qquad (5)$$

$$Q_{di} = (1 - n_{di} D_{shed})\left(\frac{x_{i,q}}{T_{i,q}} + Q_{i,0} V_i^{\beta_t}\right) \qquad (6)$$

Where, $T_{i,p}$ and T_{iq} are the time constants; P_{di} and Q_{di} are the active power and the reactive power, respectively; D_{shed} is the load shedding step size, n_{di} is the number of the load shedding steps, x_{ip} is the internal load state, α and β are load index parameters.

For the purpose of considering the scenario of long-term instability, the quasi-steady-state (QSS) approximation of (1) would be sufficient to capture the essential behavior of the system [4]. QSS replaces the short-term dynamics and concentrating on long-term phenomena, e.g. the transient dynamics of generators are neglected and thus replaced by their equilibrium equations.

B. *Off-line Optimization via JGEA*

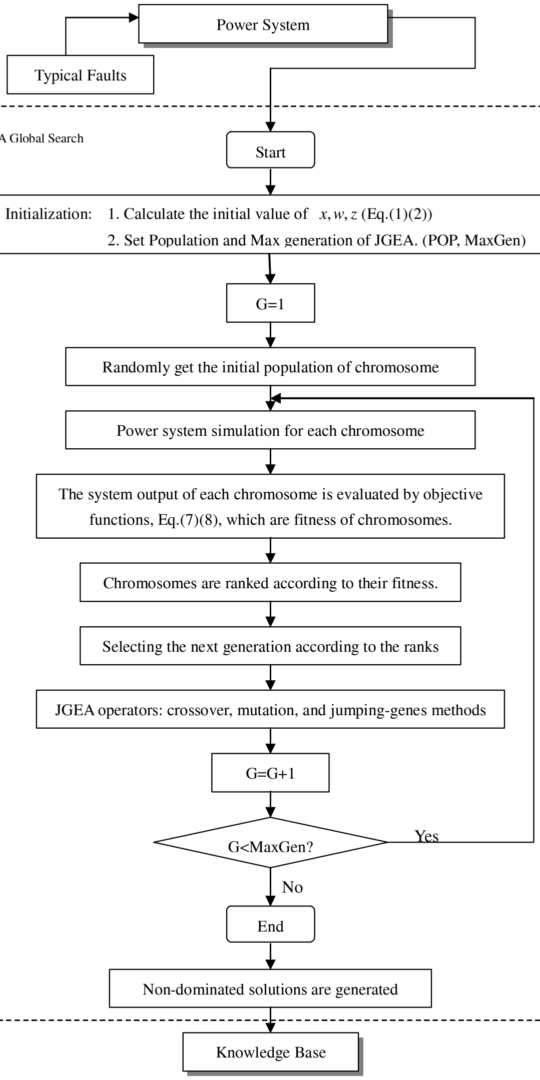
As the primary control aim of a power system is to regulate the voltage stability so that the expected voltage level is regulated and to reach the minimal variation. The control objective functions can simply be the form as follows:

$$J_{\sum vi} = \min \sum \left| v_i - v_{i_{ref}} \right| \qquad (7)$$

$$J_{act} = \min n \qquad (8)$$

where, v_i are real time bus voltages of load buses. v_{iref} are reference bus voltages of v_i . n is the number of control actions.

For the purpose of demonstrating the proposed control technique, a simple six-buses power system and the fault of increasing the impedances of transmission lines is applied as in section III. The optimization procedure was performed in an off-line fashion. A computational flow chart for searching the



required solutions is shown in Fig.2.

Fig.2 Off-line knowledge searching

The niche of this development is the non-dominated Pareto-optimal solutions created by JGEA scheme which would form a landscape of candidate control actions for all possible operations. Each of these results has its own capacity to maintain the voltage stability, and/or even to recover the voltage level when the voltage drop is deeming to appear.

The operational cycle of this formulation is no different to original genetic algorithm (GA) except that the chromosome structure consists of a multiple levels of control genes in a hierarchical fashion [11] (HGA). This formation can be translated into the context of voltage control of the power systems.

The main feature of JGEA is to allow genes in the chromosome to jump within its own genome or to other individuals in the pool. This jumping feature is now proven to be a successful operation for generating appropriate solutions particularly under multi-objective criteria scenarios. [7].

C. *Multiple Criteria Decision Making (MCDM)*

The obtained solutions can cover the whole range power control scenarios and the solutions can then be stored in a well structured KDB system for control action selection for real time operation.

Since the non-dominated Pareto-optimal solutions obtained by the use of JGEA can be numerous. A particular good choice for control action from this solution set is not easy as each solution has no preferential advantage. The MCDM scheme is adopted for this selection purpose. The decision made should then be judged on the basis of assessing the suitability and desirability of non-dominated solutions that are already stored in the KDB.

In this six-buses power system, the following five system governing criteria can be determined for the appropriate selection:

$$J_{v5} = \min\left|v_5 - v_{ref}\right| \tag{10}$$

$$J_{v6} = \min\left|v_6 - v_{ref}\right| \tag{11}$$

$$J_{\sum v5} = \min\sum \left|v_5 - v_{5ref}\right| \tag{12}$$

$$J_{\sum v6} = \min\sum \left|v_6 - v_{6ref}\right| \tag{13}$$

$$J_{act} = \min(\sum_i n_{cap} + \sum_j n_{LTC} + \sum_k n_{load}) \tag{14}$$

where v_5, v_6 are voltages of bus5 and bus6 after control interval, v_{5ref}, v_{6ref} are their reference values which are typically bus voltages before emergency happened. There are i capacitors, j load tap changers and k load shedding. $n_{cap}, n_{LTC}, n_{load}$ are moving steps of capacitors, load tap changers and load shedding respectively.

The purpose of Eq.(10) and Eq.(11) is to ensure the final steady error of the buses voltage reaches to a satisfactory level; while Eq.(12)and Eq.(13) are the measures of the instantaneous control effectiveness in terms of accuracy and speed for tracking the reference voltages. Eq.(14) represents the number of control actions which implies a reflection of economical control consideration.

The MCDM technique used in this paper is the Multi-Attribute Utility Theory (MAUT) which is the more widely applied multiple criteria methods. The basis of MAUT is the use of utility functions. Raw performance values are converted by utility functions. A more preferred performance obtains a higher utility value. Utility functions can also transform performance values of diverse criteria which are not comparable to a common, dimensionless scale.

A simple form of MAUT methods SMART is used. The desirability of each alternative solution is determined by calculating a decision score (Ep.(15)) in each criterion and multiplying this score by the weight value assigned to that criterion by the researcher or operator of a power system.

$$x_j = \sum_{i=1}^{m} w_i a_{ij}, j = 1...n \tag{15}$$

where, $x_1,...x_n$ are final ranking values of alternatives $A_1,..., A_n$. Weights $w_1,..., w_m$ reflect the relative importance of criteria $J_1,..., J_m$ and are assumed to be positive. a_{ij} is the performance of alternative A_j against criteria J_i.

In the system, performances a_{ij} are all provided by knowledge searched by JGGA. They can be easily transformed into addable values by utility functions. Weights of the criteria are usually determined on subjective basis. They represent the opinion of a single decision maker or synthesize the opinions of a group of experts using a group decision technique, as well. We use Pairwise Matrix to decide weights. This idea is borrowed from Analytic Hierarch Process (AHP) which was proposed by Saaty (1980). The methodology of AHP is based on pairwise comparisons of the following type 'How important is criterion J_i relative to criterion J_j ?'.

Once all pairs of alternatives have been compared in this way, the numeric values corresponding to the judgments made are entered into a pairwise comparison matrix. All diagonal entries are by definition equal to 1. The relative importance among criteria is the eigenvector corresponding to the maximum eigenvalue of the pairwise comparison matrix. The elements of the vector are normalized to sum to unity.

The steps for on-line selecting a suitable off-line control action via the process of MCDM can be proceeded as follows:

Step 1: *Start*: The on-line 'MCDM selection' is activated when a fault happens in the power system.

Step 2: *Set pairwise matrix M* : Compare importance between criterion.

Step 3: *Calculate weights* w_i : Obtain n-dimensional eigenvector *w* which associated with the largest eigenvalue $\lambda_{\max}$ for M .

Step 4: *Rank the non-dominated solutions*: Calculate scores of non-dominated solutions $A_1,...,A_n$, Eq.(15).

Step 5: *Selecting best solution*: The best solution A_i which has the highest score in Step 4 is identified.

Step 6: On-line *control Action*: Activate the control actions of A_i based on *Control Table*.

Step 7: Go to Step 1 if a new fault happened in the power system.

III. SIMULATION RESULTS AND DISCUSSES

A. Example system

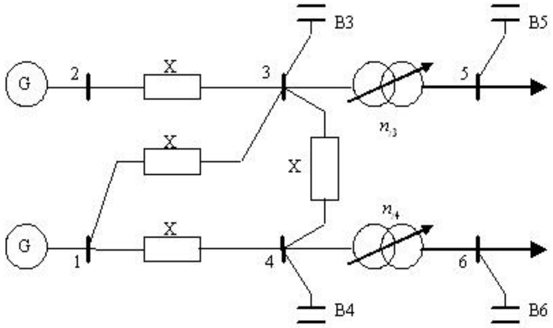


Fig.3 Six bus power system

A 6-buses power system is adopted for the purpose of demonstrating the principle of the design. The structure of the system is shown in Fig.3. It comprises of two piecewise removable loads at bus5 and bus6, four capacitors and two on-load tap changers as the control devices. These control devices operate in discrete steps. The numerous involved control parameters and system parameters are fully stated as below.

(1) Generator Parameters at Bus 2:

$P_m = 0.3p.u.$, $H = 3.54MVA/MWs$, $D = 0.0p.u.$,

$E_{f\max} = 3.5p.u.$, $E_{f\min} = -3.5p.u.$ $T_{d0}^{'} = 6.66s$, $K_{avr} = 100$

$x_d = 1.76p.u.$, $x_d^{'} = 0.42p.u.$, $x_q = 1.58p.u.$, $T_{exc} = 2.5s$,

where, P_m is the mechanical input power; D is denoted the damping factor; H is the inertia constant; $E_{f\max}$ and $E_{f\min}$ are over excitation limit; x_d is d-axis synchronous reactance; $x_d^{'}$ is d-axis transient reactance; x_q is q-axis synchronous reactance; $T_{d0}^{'}$ the transient time constants; T_{exc} is exciter time constant; K_{avr} is exciter gain.

(2) Load and Network Parameters:

$P_{05} = P_{06} = 0.6p.u.$, $Q_{05} = Q_{06} = 0.3p.u.$, $V_1 = 1.05\angle 0 p.u.$

$T_{p5} = T_{p6} = 60s$, $T_{q5} = T_{q6} = 60s$, $\alpha_{s5} = \alpha_{s6} = 0$, $T_t = 30s$

$\alpha_{l5} = \alpha_{l6} = 2$, $\beta_{s5} = \beta_{s6} = 0$, $\beta_{t5} = \beta_{t6} = 2$, $X_t = 0.1p.u.$

when $t < 15s$, $X = 0.2p.u.$; $t \geq 15s$, $X = 1.0p.u.$, X_t is the reactance of tap-changer. V_1 is the voltage at bus1.

Table.1 Parameters of Control Variables

Symbol	Actuator	Nominal value	Lower limit	Upper limit	Control step
B3	Capacitor 3	0.00p.u.	0.00 p.u.	0.30 p.u.	0.15 p.u.
B4	Capacitor 4	0.00 p.u.	0.00 p.u.	0.30 p.u.	0.15 p.u.
B5	Capacitor 5	0.00 p.u.	0.00 p.u.	0.30 p.u.	0.15 p.u.
B6	Capacitor 6	0.00 p.u.	0.00 p.u.	0.30 p.u.	0.15 p.u.
n_{T35}	LTC 3-5	1.04	0.80	1.20	0.02
n_{T46}	LTC 4-6	1.06	0.80	1.20	0.02
K_{l5}	Load shedding 5	1.00 p.u.	0.80 p.u.	1.00 p.u.	0.05 p.u.
K_{l6}	Load shedding 6	1.00 p.u.	0.80 p.u.	1.00 p.u.	0.05 p.u.

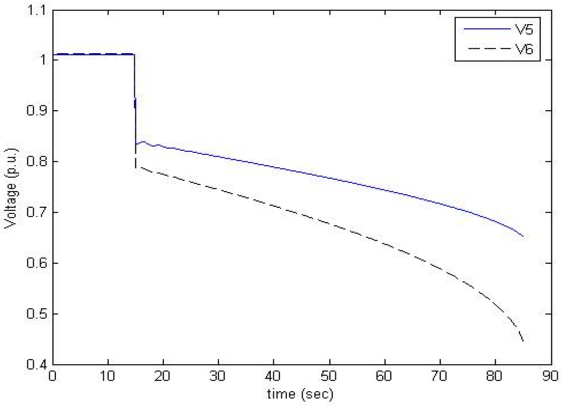


Fig.4 Simulated bus voltages breakdown at bus5 and bus6

The generator at bus1 is modeled as the infinite bus in terms of fixed voltage and voltage angle. An emergent event emerges at 15s, the impedances of the four transmission lines change from *X*=0.2p.u. to X=1.0p.u. The voltage will start to collapse if there is no proper emergency control. The trend of voltage drop appeared at bus 5 and bus 6 can be shown in Fig.4.

B. Off-line Optimization

To recover the voltage level, a 30s activation time is required for a step change of tap-changer. The activation time of all control devices are therefore assigned with equal time. The control actions may then take place at the sequence of 30s, 60s and 90s.

The proposed optimization scheme in the HGA formulation [11] can be aptly applied as the control genes that are represented by the number of bits for control device in action. The activation and deactivation of the corresponding control device as “1” or “0” respectively would determine the appropriate device used for voltage control.

When “1” is signified, the actions of tap-changers may take the form as (i) minus one step, and (ii) add one step, while the other control devices can move to any step positions between their lower limit and upper limit. This can be translated into the binary format for the control genes in the chromosome for the eventual JGEA evolutionary computation.

One parameter bit represents the movement of a capacitor and a tap-changer while two bits for one load shedding. Eight control bits for each time instance are used to decide the activity of according parameter bits.

A series of non-dominated solution sets have then been obtained for the action number n=2, 4, 6, 8 in Fig.5. These data were generated from a population pool of 50 individuals and the maximum generation was limited 50. The average computing time was around 6,507sec.

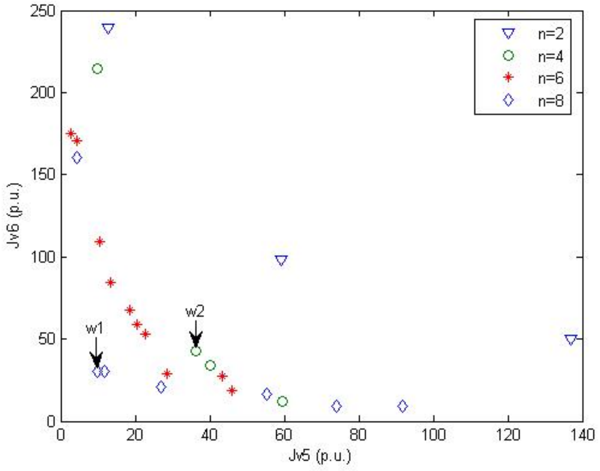


Fig.5 Non-dominated solutions of control at n=2,4,6,8

It is obvious that when n is higher, a better performance is ensured. A trade-off between performance and number of actions is therefore required in order to determine the adopted control scheme.

All these are feasible solutions for the prevention of voltage deterioration. These results signify a range of control options for adoption. The less number of control actions "n" would be preferable from the economy consideration for the cost of control actions.

C. *On-line control*

The advantage of using JGEA is its ability to search a series of feasible solutions. Based on these solutions, a suitable one for control can be selected according to defined preferences. With the knowledge stated in section III.B, an on-line control can be decided by MCDM scheme. As mentioned above in section II.C, the SMART scheme can be applied to get the required scores for non-dominated solutions while the weights of criteria are calculated by pairwise matrix.

The selection process is demonstrated under two different preferences, (i) tracing reference voltages are the most important criteria; (ii) the economic consideration which is reflected by number of control actions is more important than the other criteria.

(1) Tracing Reference Voltages are the Most Important Criteria

In Table.2, the number of control actions is considered not as important as other four criteria. The tracing reference bus voltages, $J_{\sum v5}$ and $J_{\sum v6}$, are the most important. A control action which can follow the reference voltages as soon as possible is termed as the "best" performance and will be applied on-line.

Table.2 Pairwise matrix

	J_{v5}	J_{v6}	$J_{\sum v5}$	$J_{\sum v6}$	J_{act}
J_{v5}	1	1	1/2	1/2	2
J_{v6}	1	1	1/2	1/2	2
$J_{\sum v5}$	2	2	1	1	4
$J_{\sum v6}$	2	2	1	1	4
J_{act}	1/2	1/2	1/4	1/4	1

From the matrix in Table.2, the maximum eigenvalue is 5.000. The corresponding eigenvector are [0.3123 0.3123 0.6247 0.6247 0.1562]. After a normalization process, the five weights of J_{v5}, J_{v6}, $J_{\sum v5}$, $J_{\sum v6}$ and J_{act} are $w = [0.1538, 0.1538, 0.3077, 0.3077, 0.0769]$.

With these weights of five objectives as above, the non-dominated solution 'w1' in Fig.5 has the highest score after the calculation of $x_j, j = 1,\ldots,n$ in Eq.(15). The control actions of 'w1' (Table.3) are applied to the power system on-line. The non-dominated solution 'w1' has 8 control actions. Bus voltages recover to their original values in the first control interval as shown in Fig.6.

This result reflects our preference of tracing reference voltages as soon as possible. More control actions are used in this control strategy.

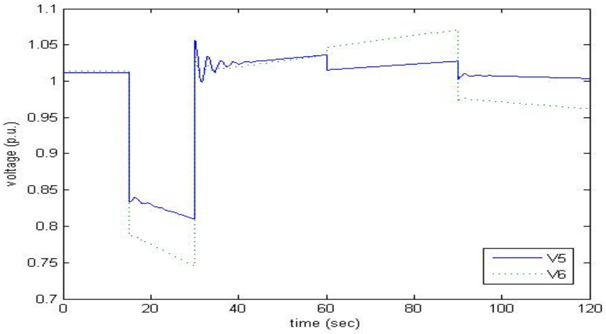


Fig.6 System performance

Table.3 System control

Time (sec)	B3	B4	B5	B6	n_{T35}	n_{T46}	K_{l5}	K_{l6}
0	0	0	0	0	1.04	1.06	0	0
30	0.15	0.3	0.3	0.15	1.02	1.06	0	0
60	0.15	0.3	0.3	0.15	1.00	1.08	0	0
90	0.15	0.3	0.3	0	1.00	1.08	0	0

(2) The Economic consideration Reflected by the Number of Control Actions is more important than

the other criteria

The number of control actions is the most important among five criteria in this situation. Then, recovery of bus voltages, J_{v5} and J_{v6}, are less important. This strategy may suitable for situations which are considered not very serious. The recovery of bus voltages can be trade off with economic objective.

Table.4 Pairwise matrix

	J_{v5}	J_{v6}	$J_{\sum v5}$	$J_{\sum v6}$	J_{act}
J_{v5}	1	1	1/2	1/2	1/3
J_{v6}	1	1	1/2	1/2	1/3
$J_{\sum v5}$	2	2	1	1	2/3
$J_{\sum v6}$	2	2	1	1	2/3
J_{act}	3	3	3/2	3/2	1

In this case, the matrix in Table.4 indicates the maximum eigenvalue is 5.000, which corresponds to the eigenvector [0.2294 0.2294 0.4588 0.4588 0.6882]. After the normalization process, the five weights of J_{v5}, J_{v6}, $J_{\sum v5}$, $J_{\sum v6}$ and J_{act} are $w =$ [0.1111, 0.1111, 0.2222, 0.2222, 0.3333].

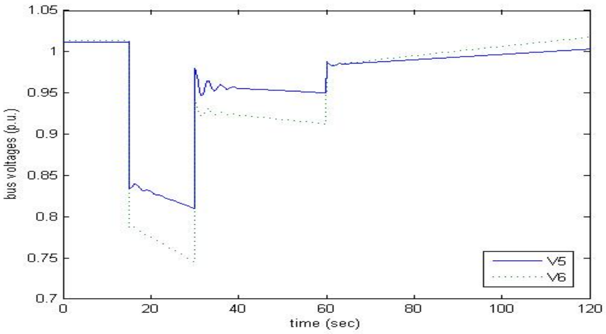


Fig.7 System performance

With the weights calculated from matrix in Table.4, non-dominated solution ‘w2’ in knowledge base (Fig.5) has the highest score. Then the according control actions are applied to the power system. Bus voltages reach their original values after two control intervals as shown in Fig.7. The control actions are listed in Table.5. Only 4 actions are used.

Compare with the first control strategies, less control actions are used.

Table.5 System control

Time (sec)	B3	B4	B5	B6	n_{T35}	n_{T46}	K_{l5}	K_{l6}
0	0	0	0	0	1.04	1.06	0	0
30	0	0	0.3	0.3	1.04	1.06	0	0
60	0	0.15	0.3	0.3	1.04	1.04	0	0
90	0	0.15	0.3	0.3	1.04	1.04	0	0

These results have demonstrated the effectiveness of the real time control of the power system based on the MCDM selection scheme and the JGEA off-line optimization method. This approach of voltage control has two distinct advantages:

(1) The control speed is very fast and can be applied to on-line control based on the off line optimization process.

(2) Upon the requirement of various preferences, the recovery from voltage drop can be operated by different control actions in accordance to the state of the optimized performance from the off line study.

IV. CONCLUSION

An off-line evolutionary JGEA optimization scheme coupled with an on-line MCDM solution selection approached as a combined control strategy for the real time control of a power voltage system. The demonstrative results via simulation on the basis of a 6-buses power system model have been proven that this can be a new and practically implemental control scheme for tackling the voltage instability problems.

REFERENCES

[1] H.Lefebvre, D.Fragnier, J.Y.Boussion, P.Mallet, M.Bulot, Secondary coordinated voltage control system: feedback of EDF, 2000, IEEE Power Engineering Society Summer Meeting, 16-20 July, Vol.1, pp:290-295

[2] S.Corsi, M.Pozzi, C.Sabelli, and A.Serrani, The Coordinated Automatic Voltage Control of the Italian transmission grid—Part I: Reasons of the Choice and Overview of the Consolidated Hierarchical System, 2004, IEEE Transactions on Power Systems, Vol.19, No.4, pp:1723-1732

[3] S.Corsi, M.Pozzi, M.Sforna, and G.Dell’Olio, The Coordinated Automatic Voltage Control of the Italian Transmission Grid—Part II: Control Apparatuses and Field Performance of the Consolidated Hierarchical System, 2004, IEEE Transactions on Power Systems, Vol.19, No.4, pp:1733-1741

[4] Mats Larsson, David J. Hill, Gustaf Olsson, Emergency Voltage Control Using Search and Predictive Control, 2002, Electrical Power and Energy Systems 24, pp:121-130.

[5] Y.Li, D.J.Hill, T.Wu, Optimal Coordinated Voltage Control of Power Systems-An Immune Algorithm Solution, Control Conference, 2004, 5th Asian, 2004, pp:1398-1403, Vol.3, 20-23 July 2004

[6] J.Y.Wen, Q.H.Wu, D.R.Turner, S.J.Cheng, J.Fitch, Optimal Coordinated Voltage Control for Power System Voltage Stability, May 2004, IEEE Transactions on Power Systems, Vol.19, No.2.

[7] T.M.Chan, K.F.Man, K.S.Tang, and S.Kwong, A Jumping Genes Paradigm for Evolutionary Multiobjective Optimization, IEEE Tran. on Evolutionary Computation, (in press) 2007.

[8] J.Fulop, Introduction to Decision Making Methods, working paper of the Laboratory of Operations Research and Decision Systems (LORDS) WP05-06, 2005

[9] V.Belton, T.J.Stewart, Multiple criteria decision analysis : an integrated approach, Boston : Kluwer Academic Publishers, c2002.

[10] David J.Hill, Nonlinear Dynamic Load Models with Recovery for Voltage Stability Studies, February 1993, IEEE Transactions on Power Systems, Vol.8, No.1, pp:166-176

[11] K.F.Man, K.S.Tang and S.Kwong “Genetic Algorithms” , 1999, Springer-Verlag London Limited, ISBN 1-85233-072-4.