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ACO based Retirement-Driven Dynamic VAR Planning for Voltage Stability Enhancement of Power Systems with High-Level Wind Power

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Abstract: *Conventional VAR compensation devices such as capacitor banks and synchronous condensers, after long periods of service, have become aged and less effective to satisfy stringent requirement of short-term voltage stability in high-level wind power penetrated power systems.STATCOMs with a rapid and dynamic reactive power support capability can be an ideal alternative, when combined with a proper equipment retirement and upgrades scheme.This work proposes a systematic approach for optimal dynamic VAR resource planning and upgrading for a power system with increased wind power penetration and equipment retirement.The problem is constituted by two parts which are aged equipment retirement and new equipment placement.A multi-objective optimization model is proposed to minimize three objectives:1) the cost of retirement and upgrades, 2) the index of proximity to steady state voltage collapse, and 3) the index of transient voltage unaccepted performance. To simulate real-world operating situation, multiple contingencies and uncertain dynamic load models are taken into account. Furthermore, Low and High Voltage Ride Through abilities for wind farms are modeled. The proposed model is tested on the New England 39-bus test system.*

Index Terms- *Multi Objective Function, STATCOMs, wind power penetration, Ant Colony Optimization.*

I. INTRODUCTION

Voltage stability is a significant concern in power system operation. When a disturbance occurs, system is likely to experience a progressive voltage drop or rapid voltage collapse, which may result in cascading failures and even wide-spread blackouts. There are several severe blackouts that have been proven directly or indirectly related to voltage stability issues [1] and [2].Regarding voltage stability enhancement concerns, seminal works like [3], [4], [5] and [6] have proposed sizing and locating of VAR sources for reactive power compensation. However, limited by technological development and their original designing purposes, these designs are becoming less effective to handle dynamic VAR support nowadays.

Today's power systems are integrating more and more renewable energy resources, such as wind power and solar power, due to a purpose of reducing emissions and dependence on fossil fuels. Wind turbines are different from conventional synchronous generators; they are more unstable and sensitive to disturbance. In order to safely consume wind farms in traditional power systems, two security requirements called Low Voltage Ride through (LVRT) and High Voltage Ride through (HVRT), denoted as LH-VRT, need to be satisfied by the wind farms following a voltage disturbance [7]. In [8], LVRT has insightfully been an objective of dynamic VAR planning in a large-scale wind integrated system. The short-term voltage stability has become a critical threat to high-wind penetrated power systems. For example, in Sep 2016, a severe state-wide blackout event occurred in South Australia (SA), and one key driven-force is that wind farms failed to successively ride through the transient voltage dip [9], [10]. It is expected that the SA system will integrate more renewable energy by 2030. In such plan, the system inertia is expected to decrease continuously, which manifests the importance and necessity of an effective dynamic VAR support. In general, with further development of renewable energy, these issues might become increasingly important and urgent, which would be beyond what current static VAR devices such as capacitor banks are capable of. Meanwhile, some equipment requires major overhauls even retirement, which would be perfect timing to schedule upgrades. For VAR devices upgrades, planners should consider static compensator (STATCOM) with faster and more adequate reactive power compensation capabilities than the current devices have as an alternative, involving the retirement planning of aged equipment.

Equipment aging is a significant problem in power systems. However, the existing methods of quantifying the uncertainty of failures are not developed enough to estimate potential losses precisely [11]. Retirement date approximation requires an enormous amount of historical data to determine a comparatively precise retirement date [12]. Among all these methods, Life Cycle Cost (LCC) is a relatively effective approach to transfer real-world aging problems into economicassessment [13]. It is generally used for an industrial investment decision making, and can also be used to make retirementdecisions backward. For example, in Victorian, Australia, some aged VAR devices have been scheduled to be overhauled or upgraded in 5 years [14]. However, in concerns of the lack of a proper planning method and high purchase cost, this plan had been deferred [15]. The proposed method based on LCC couldsolve this problem.In terms of voltage stability criterion, most of the previous works only consider one aspect, i.e., either static or short-term voltage stability[5] and [16]. A recent work of the STATCOM planning [17] has considered various types of power system stability. However, very few of them has combined the installation and retirement together as a complete progress of upgrades and in the context of wind power penetration.

To overcome the inadequacies in the existing works, this paper proposes a systematic approach for dynamic VAR upgrading planning towards future high-wind penetrated systems. The approach has five sailient features: 1) Life Cycle Cost (LCC)-based retirement and installation of dynamic VAR resources from a financial perspective, 2) optimal retirement timing to balance stability requirements and capital flow, 3) voltage stability including steady-state and short-term stability criteria to enhance the defensive capability of renewable penetrated power system against voltage instability, 4) LH-VRT capabilities to maintain a secure operation condition and increase their adaptability to power system transient disturbances, and 5) incorporating dynamic load models represented by a selected scenarios set.

The proposed methodology (Ant Colony Optimization) has been verified on the New England 39-bus system using industry-grade simulation software and dynamic models.

II. MATHEMATICAL MODELING

Fig. 1In this paper, a detailed practical economic planning model with installation and retirement is proposed. As the evaluation of them are both from a financial perspective, it is reasonable to use their combination as a financial objective as follows:

$$TC = IC + LCC \tag{1}$$

Where TC is total cost and IC is the installation cost of the new device which will be extended in detail later in the next chapter, LCC is the retirement equipment evaluation.

In this paper, LCC assessment is applied to determine the optimal retirement timing of aged devices. The equation ofLCC is defined as:

$$LCC = CI + CO + CM + CF + CD \tag{2}$$

where CI is investment cost of aged devices, CO is operation cost, CM is maintenance cost, CF is failure cost, CD is disposal cost including the remainder value of devices and disposal fee.

As theproposed method is a long-term planning, net present value (NPV) is considered:

$$NPV(C,r) = C(1+d)^{-r} \tag{3}$$

where C is the cost influenced by inflation, d is the discount rate, and r is total time. In such long-term planning, the planning horizon is divided into several stages for cash flow and decision making. The planning horizon is shown as:

$$n = S * l \tag{4}$$

where n is the total planning period, S is the chosen stage when a certain capacitor is retired, and l is the time length per stage.

Investment cost is a one-off purchase and installation of all equipment. The amount of CI is huge, and in the long term planning the influence of inflation is essential.

$$CI^{n+h} = NPV(Cost_{Investment}, n+h) \tag{5}$$

Operation cost is a sum of money spent during operation, including salaries of agents, resource purchase fee and environment tax[13].

$$CO = \sum_{i=1}^{n} LL_i * 8760 * VCR_i \tag{6}$$

Maintenance cost is an annual expenditure of maintaining performance.

$$CM = \sum_{i=1}^{n} (1+\delta)^{h+i-1} * M \tag{7}$$

Failure cost stands for those costs associated with instability. Some industries which are sensitive to the quality of power supplies would suffer an economic loss if blackouts happened. If electricity quality cannot be guaranteed, they will lose their trust in their providers. In previous research [13], [20], [21], [22], the failure cost estimation is not well-developed enough because they cannot explain why it does not increase linearly.

$$CF = \sum_{i=1}^{n} ((1+\xi)^{h+i-1} * F)((1+\lambda)^{h+i-1} * p) \tag{8}$$

Disposal cost is the expenditure to deal with the retired devices. The major components of it are a) manpower and other resources spent in uninstallation b) income of recycling:

$$CD = DC - RB \tag{9}$$

The TVSI is calculated as follows:

$$TVSI = \frac{\sum_{j=1}^{N_b} \sum_{t=T_c}^{T} TVDI_{j,t}}{N \times (T - T_c)} \quad (10)$$

The proposed model described in this section contains three objectives which are upgrade cost with retirement, steady state voltage stability index, and short-term voltage stability index. Dynamic and steady state constraints of the system are set to maintain the normal operation of power system. LH-VRT will be a major selection criterion, by which the candidate solution in any stage or under any contingency or any load condition will be eliminated immediately if unsatisfied.

$$\min_x \ \mathbf{f} = [f_1(x,u), f_2(x,u), f_3(x,u)]^T \quad (16)$$

$$f_1 = TC_1 = IC_1 + LCC_1 \quad (17)$$

$$\begin{aligned} IC_1 = & \sum_{i=1}^{H} NPV(I_i \times C_{\text{install}}, J_i * l) \\ & + \sum_{i=1}^{H} NPV(I_i \times B_i \times C_{\text{purchase}}, J_i * l) \end{aligned} \quad (18)$$

$$LCC_1 = \sum_{j=1}^{R} LCC(h + S_j * l) \quad (19)$$

$$I_i = \begin{cases} 1, & \text{if } J_i > 0 \\ 0, & \text{otherwise} \end{cases} \quad (20)$$

$$f_2 = Risk^{TVSI} = \sum_{k=1}^{C} TVSI_k \times p_k \quad (21)$$

$$f_3 = Risk^{VCPI} = \sum_{k=1}^{C} VCPI_k^T \times p_k \quad (22)$$

$$PF(P, Q, V, \theta) = 0 \quad (23)$$

$$\begin{cases} S(V,\theta) \le S^{\max}; \ V^{\min} \le V \le V^{\max} \\ P_G^{\min} \le P_G \le P_G^{\max}; \ Q_G^{\min} \le Q_G \le Q_G^{\max} \end{cases} \quad (24)$$

$$\left[\max\left(\Delta\delta_{ij}^T\right)\right]_k \le \pi \quad (25)$$

$$\begin{aligned} & V_{post}(t) - LVRT(t) \ge 0, \forall t \in T \\ & V_{post}(t) - HVRT(t) \le 0, \forall t \in T \end{aligned} \quad (26)$$

III. PROPOSED METHOD (ACO METHOD FOR OPTIMIZATION)

In The ant colony optimization algorithm (ACO) is anevolutionary meta-heuristic algorithm based on a graph representation that has been applied successfully to solvevarious hard combinatorial optimization problems. The mainidea of ACO is to model the problem as the search for aminimum cost path in a graph. Artificial ants walk through thisgraph, looking for good paths. Each ant has a rather simplebehavior so that it will typically only find rather poor-qualitypaths on its own. Better paths are found as the emergent resultof the global cooperation among ants in the colony [21].Each ant updates the pheromones deposited to the paths itfollowed after completing one tour and updates rules asfollows

$$\tau(k)_{ij} = \tau(k-1)_{ij} + \frac{0.01\theta}{J}$$

$$\tau(k)_{ij}^{worst} = \tau(k)_{ij}^{worst} - \frac{0.3\theta}{J_{worst}}$$

$$\tau(k)_{ij}^{best} = \tau(k)_{ij}^{best} + \frac{\theta}{J_{best}}$$

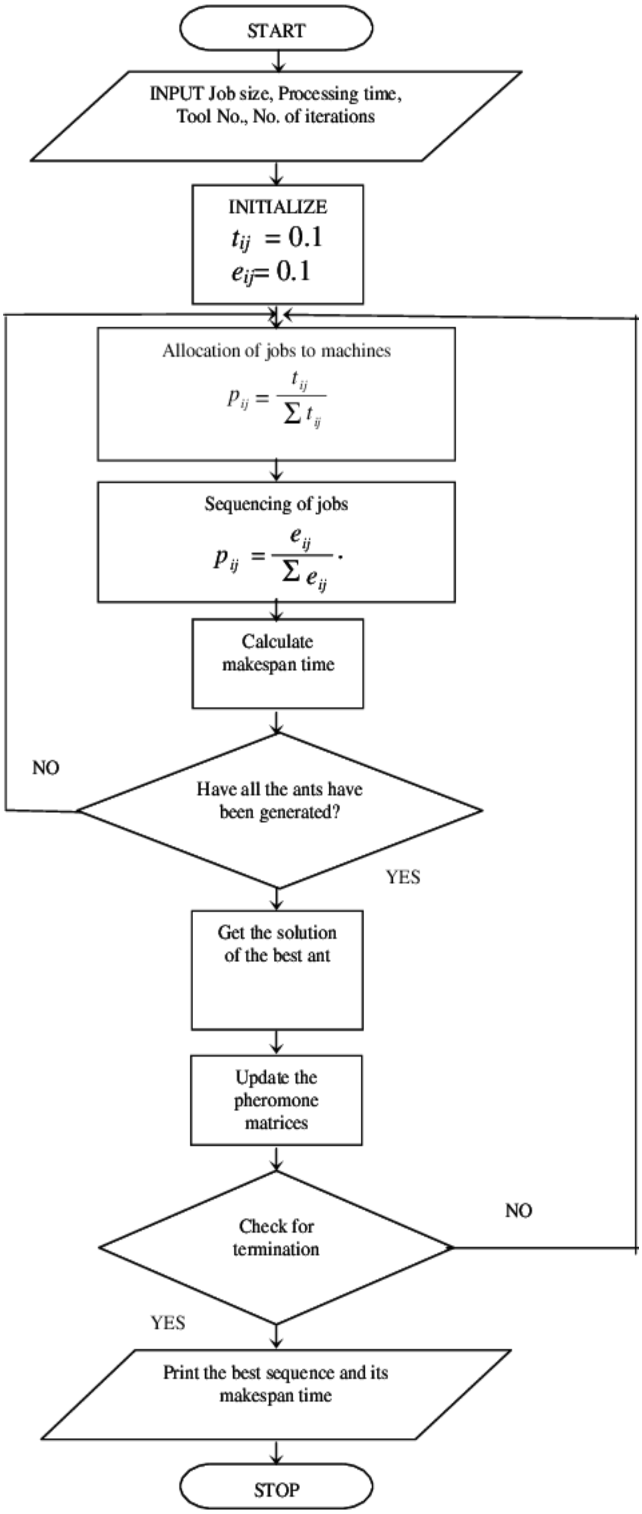

Fig.1 proposed method Implementation on Test system

The following parameters are used for carrying out the optimization design using ACO:

- Number of ants =100
- Pheromone=0.09
- Evaporation Parameter =0.65
- Positive Pheromone=0.2
- Negative Pheromone=0.1
- Maxtour=200
- Minvalue=0
- Maxvalue=1

IV. SIMULATION DIAGRAM & RESULTS

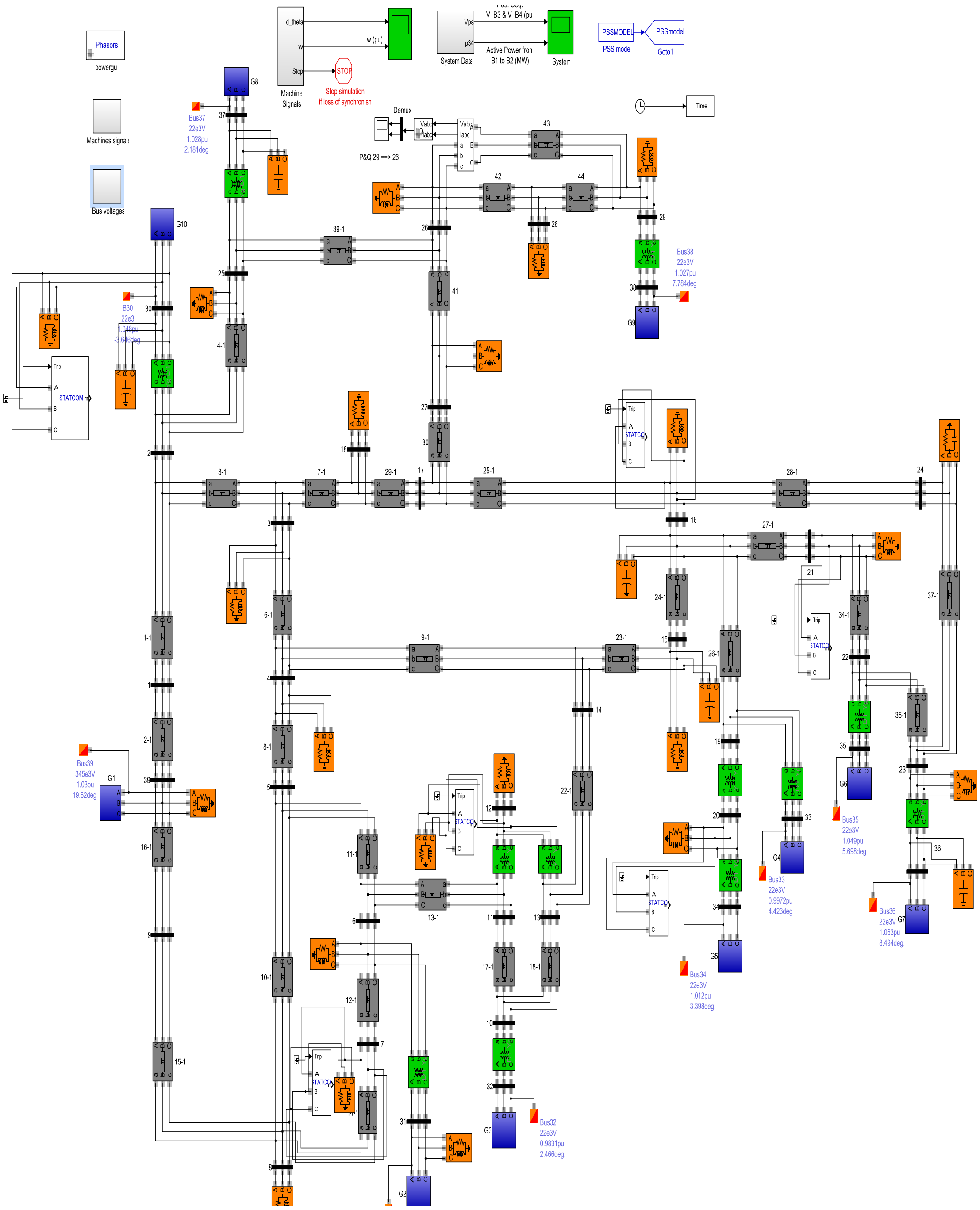

Fig.2 Simulation diagram of Test system with proposed method

The simulation diagram of proposed method is shown in fig.2. To evaluate the proposed method, 5 capacitor banks with different service ages are installed in the New England 39-Bus system [24] as Table I.Thus for each bank; the retirement decisions should be different in the simulation result. The candidate bus sensitivity result is shown in Fig. 6. Regarding the LH-VRT purpose of the wind farms on Bus 30, one STATCOM has to be placed with it. To maximize the optimization performance, the load buses will be treated as candidates. In Fig.6, bus 21 and 16 are the perfect buses because of high values of sensitivity. Bus 12 and 7 are chosen for VCPI enhancement purpose. Bus 20 is used to enhance the TVSI capability. Bus 15 are chosen to balance the distribution of MVAR in the whole system.

TABLE I
CAPACITOR BANKS PARAMETERS

Number	Bus	Capacity (MVAR)	Age (Year)
1	15	90	0
2	16	90	10
3	30	70	20
4	36	50	40
5	37	30	60

TABLE II
COLD LOAD MODEL DYNAMICS

Scenario	LM (%)	SM (%)	DL (%)	CP (%)
1	10	10	5	10
2	10	10	5	15
3	10	15	10	10
4	10	15	10	15
5	15	10	10	10
6	15	10	10	15
7	15	15	5	10
8	15	15	5	15

TABLE III
PARAMETERS OF RETIREMENT ANALYSIS

Parameters	Value
Lifetime of capacitor banks	45 years
Maintenance cost	5% of purchase cost per year
Maintenance cost increase rate	3% per year
Residual benefit of capacitor bank	5% of purchase cost per year
Disposal cost	$5000
Failure rate	8%
Increase rate of failure rate	5% per year
Penalty of failure	$0.1 million every time
Discount rate	0.05
Planning length	15 years
Planning stage	3
VCR	$2000 per MWh

TABLE IV
INSTALLATION AND UPGRADE SCHEME

Bus No	Stage 1 (MVar)	Stage 2 (MVar)	Stage 3 (MVar)
30	79	33	37
7	55	42	38
12	66	0	0
15	0	0	25
16	46	33	43
21	73	34	40
20	58	0	38

TABLE V
CAPACITOR BANKS RETIREMENT SCHEME

Bus No.	30	36	37	15	16
Stage	N/A	N/A	3	2	2

For the diversity of load dynamics, the load model composition is represented by TOAT testing scenarios. The detailed parameters in different scenarios are shown in Table II. The device purchase cost of STATCOM is $1.5 million, and the VAR compensation cost is $0.05 million/MVAR.The generator on bus 30 is changed into a wind turbine. The case is simulated on PSS@E 33.0, so the STATCOM and wind turbines are an SVSMO3U1 model and WT3 model respectively. The parameters in the LCC part are pretty hard to define, and some of them come from previous research and common sense and others can only come from imaginary and assumption [32]. All the detailed parameters are shown Table III. Regarding contingency selection, the detailed parameters come from previous research in [17].

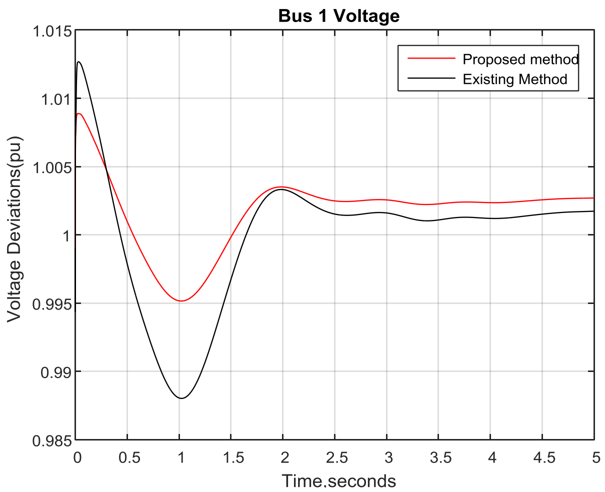

Fig.3.Dynamic Voltage profile of Bus 1 with Pareto Front method (Existing Method) & ACO method (Proposed Method)

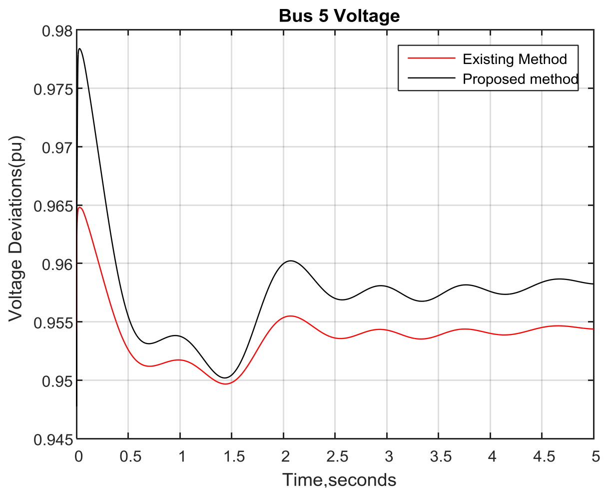

Fig.4.Dynamic Voltage profile of Bus 5 with Pareto Front method (Existing Method) & ACO method (Proposed Method)

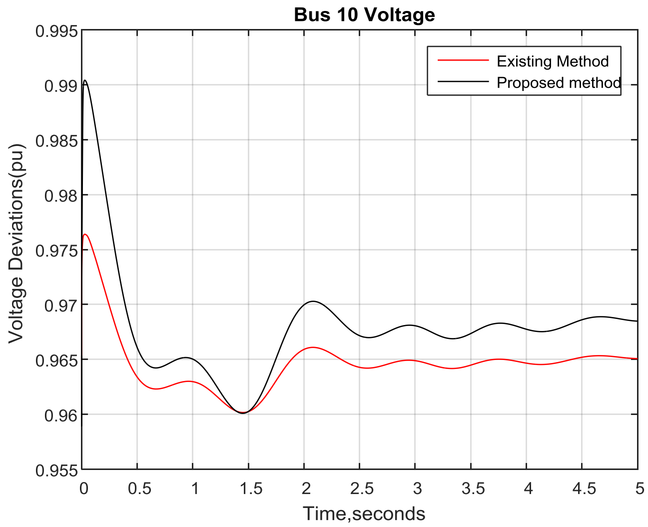

Fig.5.Dynamic Voltage profile of Bus 10 with Pareto Front method (Existing Method) & ACO method (Proposed Method)

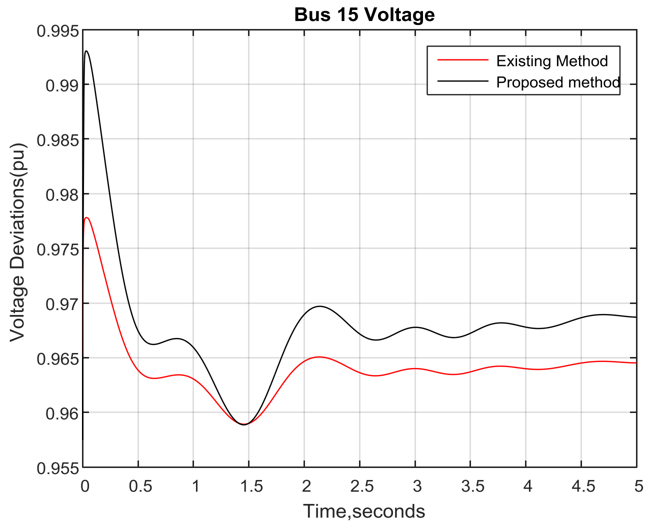

Fig.6.Dynamic Voltage profile of Bus 15 with Pareto Front method (Existing Method) & ACO method (Proposed Method)

Fig.3. shows the Dynamic Voltage profile of Bus 1 with Pareto Front method (Existing Method) & ACO method (Proposed Method).Fig.4.showsDynamic Voltage profile of Bus 5 with Pareto Front method (Existing Method) & ACO method (Proposed Method). Fig.5. shows Dynamic Voltage profile of Bus 10 with Pareto Front method (Existing Method) & ACO method (Proposed Method).Fig.6. shows Dynamic Voltage profile of Bus 15 with Pareto Front method (Existing Method) & ACO method (Proposed Method).). Fig.7. shows Dynamic Voltage profile of Bus 20 with Pareto Front method (Existing Method) & ACO method (Proposed Method).). Fig.8. shows Dynamic Voltage profile of Bus 25 with Pareto Front method (Existing Method) & ACO method (Proposed Method).). Fig.9. shows Dynamic Voltage profile of Bus 30 with Pareto Front method (Existing Method) & ACO method (Proposed Method).). Fig.10. shows Dynamic Voltage profile of Bus 35 with Pareto Front method (Existing Method) & ACO method (Proposed Method).

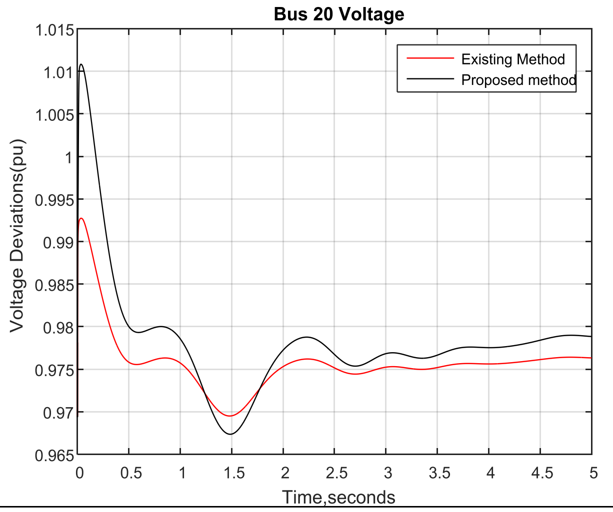

Fig.7.Dynamic Voltage profile of Bus 20 with Pareto Front method (Existing Method) & ACO method (Proposed Method)

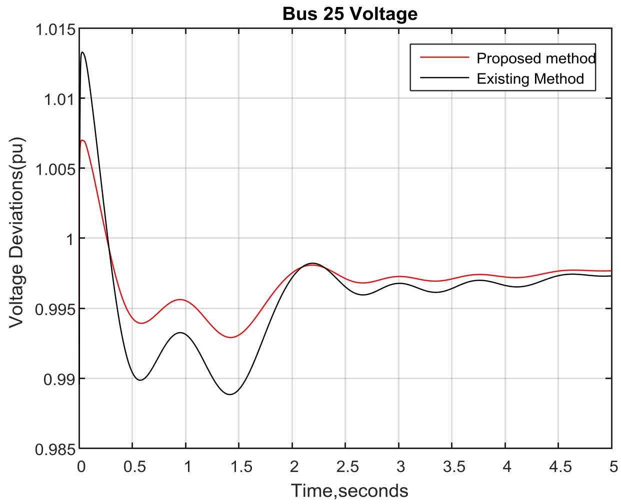

Fig.8.Dynamic Voltage profile of Bus 25 with Pareto Front method (Existing Method) & ACO method (Proposed Method)

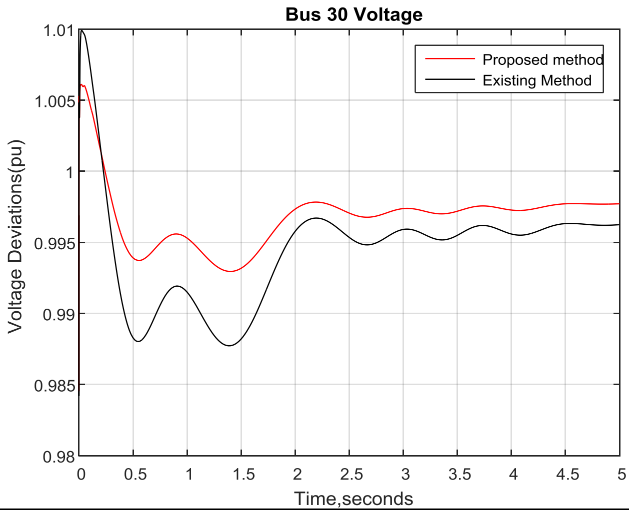

Fig.9.Dynamic Voltage profile of Bus 30 with Pareto Front method (Existing Method) & ACO method (Proposed Method)

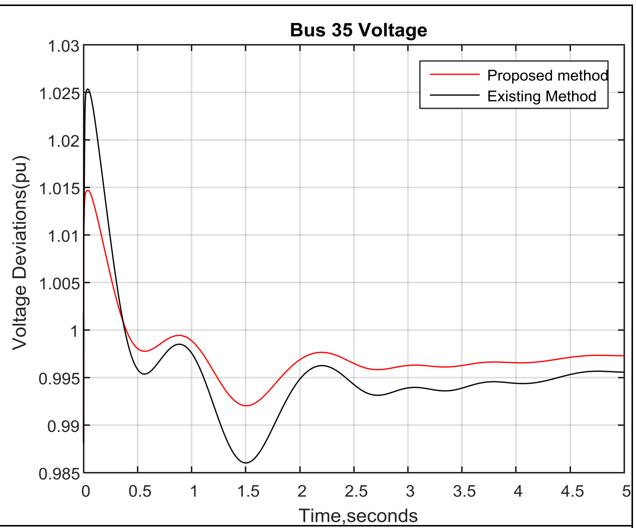

Fig.10.Dynamic Voltage profile of Bus 35 with Pareto Front method (Existing Method) & ACO method (Proposed Method)

V. CONCLUSION

This paper addresses a multi-stage planning for aged equipment retirement and STATCOM placement to enhance steady-state stability, short-term voltage stability, and voltage ride through capabilities of wind turbines under dynamic load scenarios. The problem is formulating as a multi-objective multi-stage upgrade optimization with three conflict objectives under various constraints. The proposed model has these advantages: 1) it insightfully combines the retirement planning and construction planning for the first time 2) it proposes a multi-stage planning method with upgrade decisions 3) a wind turbine is applied in the test system, and voltage ride through capabilities are modified as two constraints 4) dynamic loads scenaris are proposed in the system, which is closer to the reality. In the future, the planning model can integrate with non-network solutions from operators' perspective and more computationally efficient solution algorithms will be developed.

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