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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 paper 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*—Dynamic VAR compensation, STATCOM, wind-penetrated, dynamic load, equipment retirement planning.**

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 economic

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assessment[13]. It is generally used for an industrial investment decision making, and can also be used to make retirement decisions 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 could solve 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 penatrated 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 has been verified on the New England 39-bus system using industry-grade simulation software and dynamic models.

II. Mathematical Modelling

This section proposes a detailed planning model for dynamic VAR allocation considering equipment aging and retirement.

A. Upgrade Model with Equipment Retirement

For the industry, equipment retirement is an essential part of facility management. For those retirement activities, some devices are aged or out of date, and others might suffer from some irreparable damages. For example in [18], AEMO has planned some thermal generator retirement to improve energy structure in the future for emission reduction purpose. Although this is a critical decision in annual plan, it has not been systematically modeled in the planning process.

In 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 of LCC 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 the proposed 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.

As time goes, the average annual construction cost will decrease because of inflation and performance decline. On the other hand, the annual maintenance cost and failure cost will accordingly increase as a result of aging. The tendency of annual cost is visually illustrated in Fig.1.

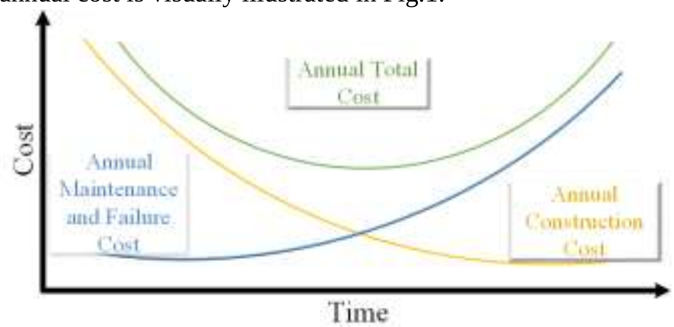

Fig. 1 Annual Cost Tendency

This paper considers five different cost terms related to equipment retirement to qualify and quantify this tendency as follows.

1) Investment cost

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.

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

where $Cost_{Investment}$ is the purchase of capacitor banks.

2) Operation cost

Operation cost is a sum of money spent during operation, including salaries of agents, resource purchase fee and environment tax[13]. In a power system, line loss cost is often used to represent operation cost. The previous research work uses the cost of production or electricity price to transfer energy into money. However, the line loss cost has a far deeper meaning than that: on the one side, it stands for the economic loss of industries due to energy loss; on the other side, it should be considered from consumers' perspective. In this case, Value of Customer Reliability [19] is used to evaluate the financial loss. VCR is the value that electricity consumers place on avoiding services interruptions, on the other hand, it could be a key valuation component valuing the benefit of expected reduce of profit from consumers' perspective. VCR is how

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much profit consumers will get from the unity electricity, which can efficiently represent the economic loss of consumers because of unserved energy:

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

where LL_i is the line loss in year i, VCR_i is Value of Costumer Reliability in year i.

3) Maintenance cost

Maintenance cost is an annual expenditure of maintaining performance. Maintenance includes component replacement, annually preventive enhancement, and corrective maintenance. It has to be applied for the whole life of equipment to maintain a healthy operating condition and extend mean life [13]. Because of long-term continuously serving, the performance of equipment will get worse, and it is also harder and harder to restore it to its best performance. So, the maintenance cost will increase annually. In this case, there is an even increasing model to estimate the real world situation.

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

where M is the maintenance rate, δ is the increase rate of maintenance cost, h is the age of the device.

4) Failure cost

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. When dividing it into fault probabilities and economic loss per fault, it is revealed that failure cost should increase quadratically. The probabilities increase annually because of aging issues, and consequences also become more severe because load capacity, electricity price, system topology are changed as time goes by.

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

where F is the penalty factor (Eg. 100000), ξ is the load increase rate, p is the probability of contingency, λ is the increase rate of p because of aging.

5) Disposal cost

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:

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

where DC is the disposal cost including uninstallation fee, RB is the residual benefit from selling the retired device.

B. Voltage Stability Indices

The voltage stability is concerned on different aspects depending on various timescale of system characteristics of interests. In most previous works, only one aspect is considered, i.e., short-term voltage stability or steady-state stability. In this paper, both criteria are deemed to reflect the effect of dynamic VAR compensation fully.

1) Short-term Criterion

Short-term stability needs to address several concerns including delayed voltage recovery, unacceptable voltage deviation, and voltage collapse. Some industrial criteria reported in [23], like Mid-Continent Area Power Pool and Wisconsin Public Service Corporation Criteria, only define the unacceptable voltage dip magnitude and the duration, and can only provide a binary decision to the short-term voltage stability which is, stable or unstable. In comparison with them, in [24], an index to evaluate the severity of voltage vibration after clearing contingencies is proposed for quantification assessment of short-term voltage stability. From establishing a factor called Transient Voltage Severity Index (TVSI) and summing them all, this method is able to quantify voltage stability performance on a continuous basis [24]. The effectiveness of this index has been verified in our previous work [24] and [17], and referred in recent works [5] and [25].

The TVSI is calculated as follows:

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

where N_b is the number of system buses, T is a transient period, T_c is fault clearing time, $TVDI$ is Transient Voltage Deviation Index which is calculated by the system post-contingency simulation in time domain:

$$TVDI_{j,t} = \begin{cases} \frac{|V_{j,t} - V_{j,0}|}{V_{j,0}}, & \text{if } \frac{|V_{j,t} - V_{j,0}|}{V_{j,0}} \geq \eta \\ 0, & \text{otherwise} \end{cases} \quad \forall t \in [T_c, T] \tag{11}$$

where $V_{j,t}$ is voltage magnitude of bus j at time t, and η is the threshold to evaluate if the chosen voltage magnitude is acceptable.

2) Static Criterion

The second aspect of voltage stability considered in this paper is steady-state voltage performance. For static voltage stability, which mainly focuses on the power transfer capability of power networks, or the existence of the system equilibrium after or without a contingency. Therefore, the analysis mostly concentrates on evaluating the proximity to instability for a system. The most commonly used static voltage stability evaluation measure is the loadability margin (LM) [1]. However, it requires defining a certain load and generation increment direction, which is very difficult to predict in long-term network reinforcement stage. Importantly, the LM can be quite sensitive to the variation of loading patterns. Without the knowledge of accurate loading patterns, the dynamic VAR planning results can be unreliable. In this paper, the steady-state stability is measured through the Voltage Collapse Proximity Indicator (VCPI) which is based on

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maximum power transfer theory[26]. VCPI evaluation with its advantages is a well-developed method to represent the proximity to instability. In comparison with LM, VCPI is only system-dependent and does not require a load and generation increment direction, which is suitable for planning study.

$$P_{r(\max)} = \frac{V_S^2}{Z_S}\frac{\cos\phi}{4\cos^2\left((\theta-\phi)/2\right)} \tag{12}$$

$$Q_{r(\max)} = \frac{V_S^2}{Z_S}\frac{\sin\phi}{4\cos^2\left((\theta-\phi)/2\right)} \tag{13}$$

$$VCPI\left(power\right) = \frac{P_r}{P_{r(\max)}} = \frac{Q_r}{Q_{r(\max)}} \tag{14}$$

where P_r and Q_r are respectively the active and reactive power delivered to the receiving terminal, $P_{r(\max)}$ and $Q_{r(\max)}$ are respectively the maximum delivery capability of active and reactive power. V_S is voltage magnitude calculated from power flow result, and Z_S is line impedance, θ is line impedance angle and ϕ is load impedance angle.

$$VCPI^T = \sum_{l=1}^{L} VCPI\left(power\right)_l \tag{15}$$

when STATCOMs plugged into a bus, it will reduce Q_r as it provides reactive power, as well as angle ϕ.

C. Low Voltage Ride Through and High Voltage Ride Through for wind turbines

LVRT capability is one of the key requirements for wind power integration. When there is a severe voltage drop, if voltage magnitude fails to recover to its safe level in time, or even worse stays at a lower magnitude, the wind farm would be cut off from the grid. As in this case, the insecure operation of wind farm would cause several cascading consequences like large scale power unbalance, frequency damping, and losing synchronism, so the cut off would be necessary. There would be cost and energy waste if cut off, so it is essential for a wind farm to enhance LVRT capabilities to get through these contingencies. Especially for high wind penetrated systems, like SA system [10], where the renewable energy has already reached 40% of the total generation, the trip-off of wind farms will cause a huge amount of economic loss and wide area blackout. In SA system, the non-network solutions, like under voltage load shedding, has react multiple times, however, they are still not enough for this system because of the lack of system inertia, so the blackout occurred anyway. In this situation, the additional reactive power supply will be extremely essential, and STATCOM is suitable for this due to its fast speed of response.

Most previous research has put emphasis on LVRT. However, there is little concentration on HVRT which can also cause trips of wind plants. When a contingency happens and then protective devices are triggered, the voltage magnitude might suddenly increase to an unacceptable level if overcompensated, which causes negative consequences for both systems and wind turbines. The latest version of Voltage Ride Through White Paper has involved HVRT in WECC standard as Fig.2, which means that the significance of HVRT has been recognized [7]. This model manipulates the potential of HVRT and will place emphasis on it as well. It can guarantee the proper correction of voltage control to avoid further contingencies like overcompensation, and it will also help to accelerate convergence speed during optimization procedure.

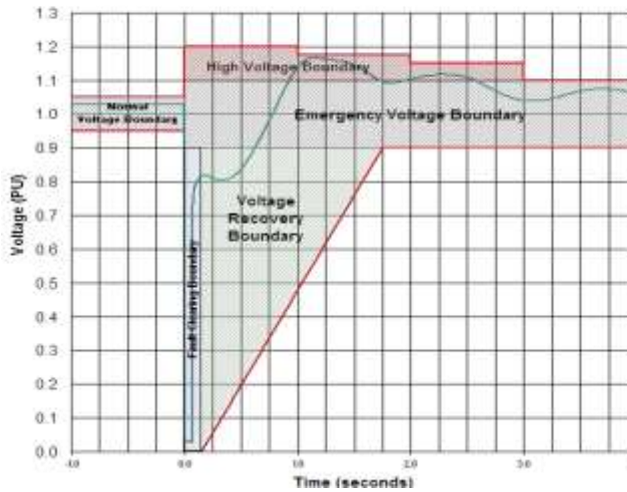

Fig. 2 Wind Turbine Voltage Ride Through Profile

D. Dynamic Load models

Generally, the uncertainties of system load and wind farm output are very important concerns for online operation phase. The proposed method focuses on planning problem, so the peak loading/generation scenario can be applied to reflect the most loading condition. Although it may be conservative, the voltage stability is a very stringent constraint in practice and has to be satisfied. On the other hand, the prediction of a certain load/generation scenario in a long-term planning is very hard to be accurate, so in this paper, the load/generation is set to be peak and the proposed method put emphasis on load dynamics uncertainty.

For voltage instability problems, the load dynamics plays a critical role and a key driven force, therefore, the dynamic load models should be considered in VAR planning. Some researchers have built a dynamic load model which contains diverse static and dynamic loads to simulate the actual grid better than conventional static load models [27], as the actual characteristics of the load in the real world are stochastic and time-varying. The “CLOD” [28] load is used in this paper to specify load characteristics. It contains eight kinds of load, including large motors (LM), small motors (SM), discharge lighting (DL), transformer exciting current (TX), constant power load (CP), voltage-dependent real power load and branch impedance, shown in Fig.3.

In order to model load uncertainty, this paper applies a robust design technique called *Taguchi*’s orthogonal array testing (TOAT) [29] to select a representative set of load model scenarios to approximate the whole uncertainty space, which is more efficient than other techniques like Monte Carlo sampling. Firstly, an uncertainty space is determined by the number of variables and representative levels, but sometimes it would be unaffordable if there are too many variables. Under the TOAT criterion, the uncertainty space is expressed by several scenarios calculated by a matrix called orthogonal arrays (OA), whose number of rows and columns are combinations of levels and number of variables, and the number of matrix levels are determined by representative levels [29]. Detailed description of TOAT can be found in [21].

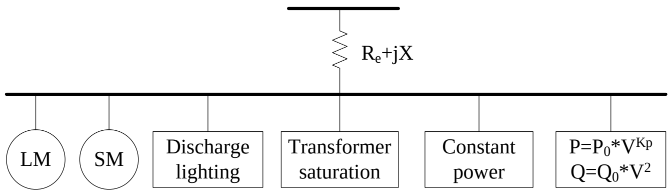

Fig. 3 Dynamic load model COLD

III. Multi-Objective Optimization Model

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.

A. Objectives

$$\min_{x} \ \mathbf{f}=\left[f_1(x,u), f_2(x,u), f_3(x,u)\right]^T \tag{16}$$

where χ and u are decision variables and state variables. The variable χ contains STATCOM location, STATCOM size and retirement time of aged capacitor bank,

The first objective f_1 is the economic analysis including LCC cost of capacitors and investment cost of STATCOM, which is the output of Eq. (1), and the aim is minimizing the overall cost, so it is better to combine them into one objective. With this method, it is easier for the optimization progress to determine decisions as they are in the same dimension.

$$f_1 = TC_1 = IC_1 + LCC_1 \tag{17}$$

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

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

where J is decision variable of STATCOM whose initial value is zero, and S is decision variable of retirement whose initial value is maximum stage. The matrix I is a binary decision variable of STATCOM calculated from a variable J .

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

The second and third objective function, f_2 and f_3 , respectively stand for the risk level for short-term voltage stability and steady-state stability. In these objective functions, risk-based criteria to quantify the contingency impact are introduced which contains the influence of multiple contingencies and their probability. Meanwhile, it will reveal the real performance of STATCOM placement in a dynamic condition.

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

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

where p_k is contingency probability calculated from historical failure record and C is the number of contingencies.

B. Dynamic and Steady- State Constraints

In the power system, steady state constraints and dynamic constraints are needed. The steady-state constraint, is power flow equilibrium, reactive power balance and so on.

$$PF(P,Q,V,\theta) = 0 \tag{23}$$

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

where these two equations represent power balance (both active and reactive power) and operational limits including voltage magnitude, line limitation, and maximum generation limit.

In term of dynamic constraints, it consists of multiple factors for requirements of safe generators operation. In this paper, dynamic constraint rules that rotor angle deviation will not rise beyond a certain threshold under any contingency. Otherwise, the generators will be tripped by relays.

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

where $\left[\max\left(\Delta\delta_{ij}^T\right)\right]_k$ represents, the maximum rotor angle deviation between any two generators for contingency *k*, in the transient period *T* and π is a threshold for an extreme situation.

C. Low Voltage Ride Through and High Voltage Ride Through Constraints

The LH-VRT profile is transferred into a set of voltage magnitude value. When got post-contingency voltage set in an order of time, it will be compared with corresponding LH-VRT magnitude. If the post-contingency voltage magnitude at any time is lower (higher) than the corresponding LVRT (HVRT) value, the candidate solution will be eliminated.

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

where V_{post} is the post-contingency voltage profile. LH-VRT constraint is a conclusive constraint which means the candidate solution without a positive result will be eliminated. This criterion is binary and strict, because according to most of the grid codes [15], if a wind farm fails to satisfy LH-VRT, it will be definitely cut off from the grid to align with the industry requirements.

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IV. SOLUTION METHODOLOGY

A. Candidate Bus Selection

One major part of initialization is candidate bus selection, which can effectively reduce the computation burden. In this paper, a trajectory sensitivity analysis [17] method is applied to filter the candidate buses. The sensitivity of objective function, f_2 and f_3 should be chosen to apply sensitivity analysis.

$$Sen_i\left(f_2\right)=\frac{f_2\left(B_i\right)-f_2\left(B_i+\Delta B\right)}{\Delta B} \tag{27}$$

$$Sen_i\left(f_3\right)=\frac{f_3\left(B_i\right)-f_3\left(B_i+\Delta B\right)}{\Delta B} \tag{28}$$

where B_i is the capacity of STATCOM at bus i and ΔB is unity size of STATCOM, e.g., 5 MVar.

If a bus has a bigger sensitivity, it would have a better voltage stability performance if a STATCOM is placed on this bus, and this bus has a potential to be candidate buses.

B. Pareto frontier

Indifferent to those single objective optimization problems having the only optimal answer, multi-objective ones usually fail to determine a certain solution that can be optimal for all objectives synchronously. As their objectives are often in conflict with each other, these problems require a series of trade-off answers. For decision makers, they can choose from industrial perspective amongst all these solutions.

Trade-off solutions can be defined by a concept called *Pareto optimality* theory [30], based on which in the feasible decision space there is no objective function can be further optimized without causing degradation of others. The chosen solutions based on *Pareto optimality* theory are called *Pareto optimal*, and all vectors of these solutions compose *Pareto Front*. In this paper, a powerful multi-objective programming algorithm NSGA-II [31]is applied to determine Pareto Front.

C. Coding Rule

As one of the most widely-used multi-objective evolutionary algorithms, NSGA-II is an enhanced version of NSGA. It consists of a repaid non-dominated searching scheme and a simple but effective bionics method, in which every solution is called a gene and works under natural selection and evolution. Each gene for this problem should follow coding rules shown in Fig. 4. The letter *J*, *B*, and *S* stand for installation decision matrix, STATCOM capacity matrix, and capacitor retirement decision matrix respectively for each candidate bus.

The first sector of the gene contains three parts representing each planning stage, and each part has two sets of integer, the first set stands for the binary decision variables, and the corresponding number in the second set is its capacity. The second and third parts refer upgrades. For example, for a certain STATCOM, if it has been constructed in stage one, the positive result of stage two or three will be an upgrade decision. Otherwise, it will be a construction decision at that stage.

In the second sector part, capacitor banks retirement is a one-off decision, which number means the stage of retirement ranging from 1 to 4. The initial value of each gene is the maximum stage of planning, and if the final result is unchanged, it means that the capacitor bank in this bus has not been retired at the end of planning year.

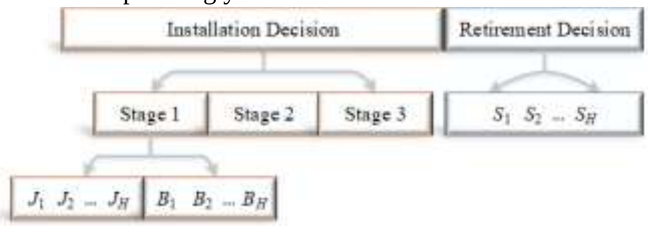

Fig. 4 An Individual Code Structure

D. Computational Flowchart

The overall computational framework is proposed as Fig.5.

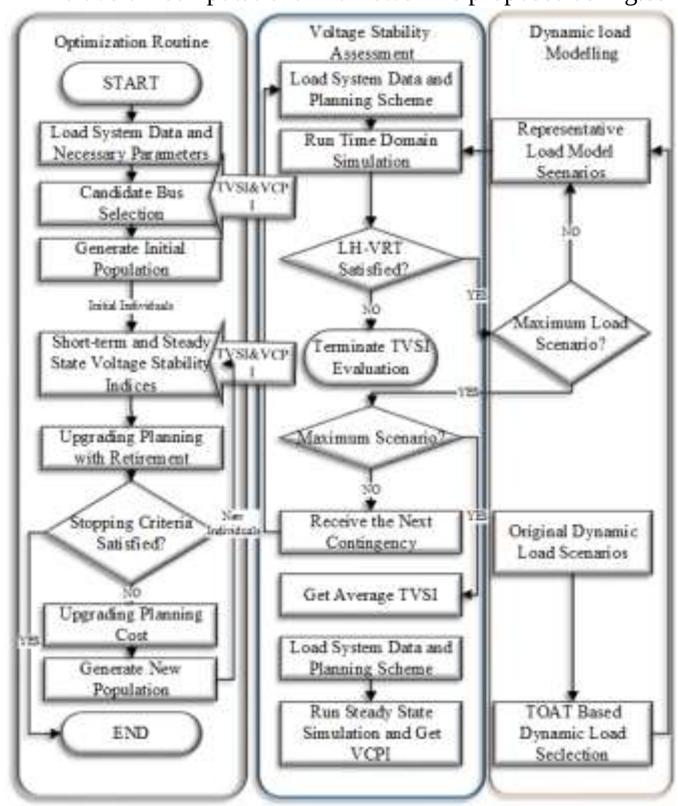

Fig. 5 The Flowchart of Proposed Method

The computation includes the following steps:

1) *Initialization*: system data input and candidate bus selection based on TVSI&VCPI sensitivity analysis.

2) *Main procedure*: Loop the main optimization precedure.

3)*Voltage stability analysis*: Test each candidate in voltage stability module under various load scenarios.

4) *Candidate Evaluation*: Return results of voltage stability indices calculation for each contingency under each dynamic load condition to main procedure. The output is the feedback of the feasibility of the candidate solution. The average stability results will be integrated with total cost as objectives.

5) *Break criterion*: In any step, if LH-VRT are violated, the estimation of the candidate solution will be terminated.

6) *Termination*: If the stopping criteria is satisfied, the main procedure will stop and return the final optimization result.

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V. Simulation Results

A. Test System

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.

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

B. Candidate Bus Sensitivity

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.

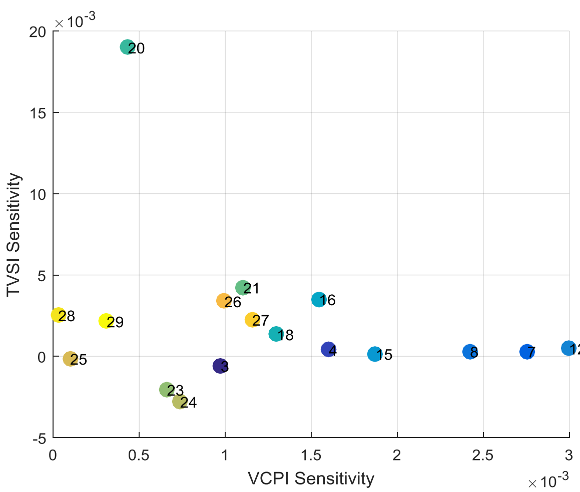

Fig. 6 Candidate Bus Sensitivity

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

C. Dynamic Load of COLD Load Model

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.

D. Other Parameters

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.

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

Regarding contingency selection, the detailed parameters come from previous research in [17]. With all settings mentioned above, the test system is shown in Fig. 7.

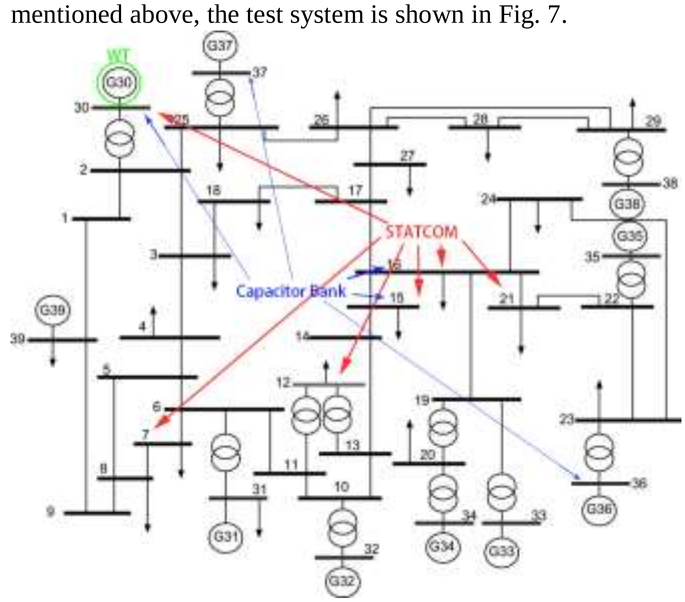

Fig. 7 One-line diagram of the New England 39-bus system

A desktop computer with Intel(R) Core(TM) I5-4590 CPU @ 3.30Ghz and RAM 8.00GB is used to run the simulation. Each time domain simulation is about 54 second on average, and the whole computation process takes around 120 hours for a 15-year retirement and upgrades planning result. Note that the planning problem is offline practiced, which is not time-restricted in contrast to the operation problem. The solution process can be speedup by a parallel computing platform such as one designed in [33].

E. Simulation Result and Pareto Frontier

A Pareto Front in Fig. 8 with various solutions is obtained after simulation, which represents the trade-off cost-benefit choices of planning. For decision-making from the industrial perspective, these candidates are much more valuable than a single one, which may provide a margin for their industrial profit.

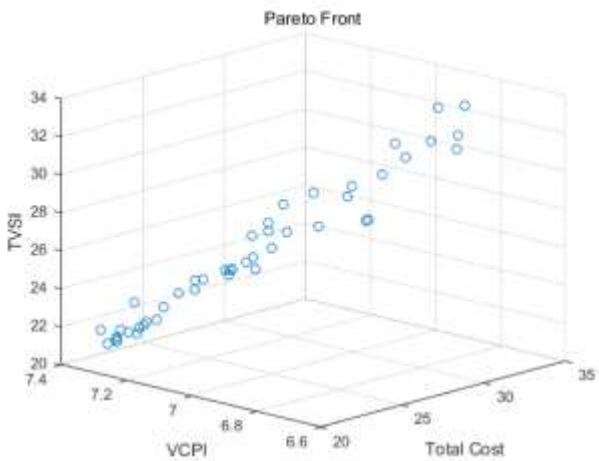

Fig. 8 Pareto Front

From the Pareto Front, planning with high stability comes with the high cost of devices installation and aged equipment overhauls. The motivation of retiring aged devices is the occurrence of unfixable failures. However, those putting off decisions put the system and customer in a high risk of failure. From the simulation result, putting off the retirement may earn short-term profit but will cause an overall loss of benefit. Meanwhile, decision-makers also can choose their preferable solutions from their personal or industrial requirement.

In order to choose an optimal solution, the lowest acceptable value of stability should be determined and then choose the solution with the lowest investment cost. Under this criterion, the 26th solution in the Pareto Front is chosen which are shown in Table IV, Table V and Table VI.

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

TABLE VI
SIMULATION RESULT

Objective	Total Cost	VCPI	TVSI
Value	$27.31 m	6.972	0.6562

The voltage profile of chosen solution is shown in Fig.9. From Fig. 9, it can be determined that the short-term voltage stability is enhanced significantly, and Bus 30 has succeeded to get through the LH-VRT requirements. Table VII compares the proposed method and the state-of-the-arts in the literature. As can be seen, for the existing methods, equipment retirement has not been considered, and very few of them has taken long-term multi-stage planning, dynamic load scenarios, and wind energy into account. However, these considerations are more than valuable in the real world planning, without which the planning results have to be re-adjusted to cater the requirements of industries before application. As a result, in comparison to others, the performance of the proposed method has its superiority and contribution, which makes it a more comprehensive planning method. Regarding the computation burden, the proposed method relies on the TOAT to select the minimum number of representative scenarios to approximate dynamic load model uncertainty. Therefore, it has much less computation burden than conventional Monte Carlo simulation methods. On the other hand, due to the use of NSGA-II, its overall computational burden is heavier than classic programming algorithms. But it should be indicated that the computation time is not a major concern for planning problem.

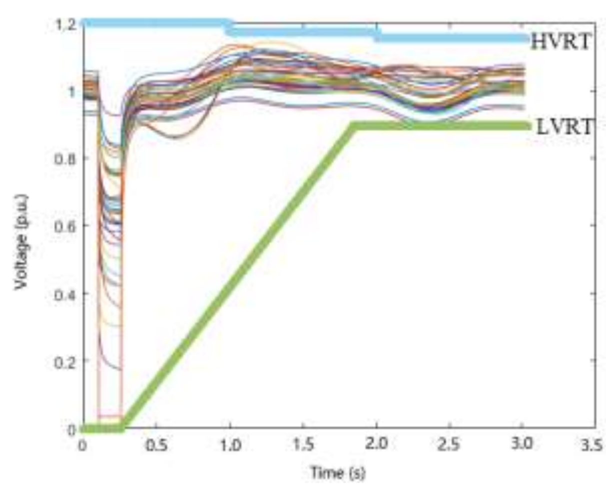

Fig. 9 Illustration of Dynamic Voltage Profile

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TABLE VII
THE COMPARISON OF THE PROPOSED METHOD AND PREVIOUS RESEARCH

	Proposed Method	Ref [5]	Ref [6]	Ref [17]	Ref [24]
Wind power penetration	√	×	√	×	×
Dynamic load modelling	√	×	√	×	×
Multi-stage horizon planning	√	×	√	×	×
Equipment retirement	√	×	×	×	×
Static voltage stability	√	×	√	√	×
Short-term voltage stability	√	√	×	√	√
Computation burden	Medium	Low	Low	High	High

VI. CONCLUSION AND FUTURE WORK

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 sceanrios 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 algorihtms will be developed.

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