The multi-objective optimal allocation method of static var compensator based on transient voltage security control

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Abstract. Based on the detailed consideration of the dynamic characteristics of Static Var Compensator (SVC), the mathematical method for installing location and optimal capacity of SVC considering transient voltage security is proposed. Firstly, the trajectory sensitivity index is used to determine the key fault set and SVC candidate location. Then, transient voltage security constraint of the bus voltage is restored to 0.75pu within 1s and the bus voltage is restored to 0.9pu within 3s after remove fault. Finally, considering the transient voltage recovery characteristics and dynamic characteristics of SVC, the minimum of bus voltage deviation after fault removed and minimum of installation capacity of SVC as objective function for hybrid optimal allocation model. The bus voltage and capacity of SVC are introduced as variables into the Crisscross Optimization Algorithm (CSO) for solving. The effectiveness of the proposed SVC installation location and capacity optimization method is verified by the time domain simulation of the IEEE39-bus system.

1. Introduction
In the transient process of power system with large disturbances, such as short fault and broken line, the bus voltage will generally have a great deviation. In the process of voltage drop, the reactive power absorbed by induction motor load will increase, which will further aggravate the voltage drop of load bus [1]. Moreover, the voltage drop to a certain limit will lead to the blockage of induction motor, the dramatic increase of reactive power absorbed from the power system, the occurrence of phenomena such as the action of protective or safety automatic devices, the abnormal operation of power electronic devices, and even the transient voltage instability of the power system. Therefore, it is generally required that the power system can ensure that the duration of the load bus voltage below a given value does not exceed a predetermined period of time after fault, otherwise the voltage is considered to be transient unsafe [2].

There are two kinds of transient voltage safety control: preventive control and emergency control. Transient voltage safety emergency control is implemented after detecting a fault in the power system, the transient voltage insecurity is corrected to the transient voltage safety state after the fault in power system. Dynamic reactive power compensation devices, represented by SVC, due to the fast controllability, it's very suitable for improving transient safety of power systems [3-10]. The SVC is installed in the load area of the system, which can quickly provide dynamic voltage support to the load bus after the fault, so as to prevent voltage collapse. Choosing the suitable installation location and capacity is the precondition of giving full play role of SVC, which has important practical significance.
In this paper, considering the dynamic characteristics of induction motor load and considering the multi-fault condition, the multi-objective optimal allocation model and method of SVC for transient voltage security and stability control are established, we treat the minimum of bus voltage deviation after fault recovery and minimum of installation capacity for SVC as objective function. The voltage of each bus and the installation capacity of SVC are introduced as variables into the Crossover Optimization Algorithm to solving the model. Finally, the proposed SVC optimal allocation method effectiveness is verified through time domain simulation of IEEE39-bus system.

2. SVC optimal allocation model

2.1. Installation location determination of SVC

The steps to determine the installation location of SVC are as follows:

1) According to voltage stability margin index method, determine the critical fault sets \( \{F_1, F_2, ..., F_N\} \) which threaten the transient voltage security and stability of power system [11]. According to the recovery level of bus voltage during the fault period, the SVC installed is preliminarily determined in bus \( \{1, 2, ..., m\} \).

2) SVC is installed on each bus to be selected, and time domain simulation of key faults is carried out again.

3) From the first two steps of time domain transient simulation results, the voltage-reactive power trajectory sensitivity index \( TS_i \) for bus \( j (j=1, 2, ..., m) \) is calculated according to Reference [6].

4) The selected buses are sorted according to \( TS_i \), and the maximum trajectory sensitivity index value is the optimal installed buses for SVC.

2.2. SVC capacity optimal model

When the power system is faced with transient voltage security and stability problems after large disturbances, it is necessary to optimize multi-objectives and coordinated multiple control to implement optimal coordinated emergency control from the perspective of centralized control. This problem can be described as a multi-objective hybrid optimal model in the following form:

\[
\begin{align*}
\min & \quad [J_1, J_2] \\
\text{s.t.} & \quad \frac{dx}{dt} = f(x(t), y(t), u(t), v(t)) \quad (1.2) \\
& \quad g(x(t), y(t), u(t), v(t)) = 0 \quad (1.3) \\
& \quad x_{\min} \leq x(t) \leq x_{\max} \quad (1.4) \\
& \quad x_{\min} \leq y(t) \leq x_{\max} \quad (1.5) \\
& \quad x_{\min} \leq u(t) \leq x_{\max} \quad (1.6) \\
& \quad v(t) \in \Omega \quad (1.7)
\end{align*}
\]

Formula (1) can describe the dynamic process of components in power system, including the dynamics of generator and its excitation system, load and SVC.

In Formula (1.1): \( J_1 \) and \( J_2 \) are objective functions.

Formulas (1.2) and (1.3) represent differential-algebraic equations describing the transient voltage dynamic process of power system, \( x \) and \( y \) represent all state variables and all algebraic variables of the power system respectively; \( u \) represents the continuous control variables for the implementation of transient voltage safety and stability control, and in this paper, it is the regulation of bus voltage area curve; \( v \) represents the discrete control variables for the implementation of transient voltage safety and stability control, and in this paper, it is the installing capacity of SVC.

Formula (1.4) to (1.7) represent constraints imposed on variables of the power system. Among them, \( x_{\max} \) and \( x_{\min} \) represent the upper and lower bounds of power system state variables, including...
some limiting links in excitation control system, $y_{\text{max}}$ and $y_{\text{min}}$ represent upper and lower bounds of algebraic equation variables, including acceptable constraints on bus transient voltage sags; according to the China’s standard, the constraint is set to restore the voltage above 0.75pu after 1s of fault removed; $u_{\text{max}}$ and $u_{\text{min}}$ represent the upper and lower limits of continuous control variables, in this paper, it is the upper and lower limits of the reference value of excitation voltage are regulated; $\Omega$ represents the set of discrete control variables, in this paper, it is the installation location combination of SVC.

2.2.1. The first objective function. The objective function $J_1$ is defined as the sum of squares of bus voltage deviation. The compensation effect of SVC is directly reflected in the transient voltage recovery characteristic curves. Generally speaking, the larger the dynamic reactive power compensation, the faster the transient voltage recovery. Within 3s of fault removed, the area $S$ of voltage sags on $V$-$t$ characteristic curves of all buses in the power system are smaller. After fault removed, the area $S_i$ of voltage sag on $V$-$t$ characteristic curve during voltage recovery is the shaded part, shown in Figure 1.

According to the above description, the objective function $J_1$ can be set as:

$$
\min \ S = \sum_{i=1}^{n} S_i = \sum_{i=1}^{n} \int_{t_c}^{t_{c+i}} (U_i - U_{\text{t,p}})^2 \, dt
$$

(2)

In the Formula (2):
- $i=1, 2, \ldots, n$;
- $n$ is the total number of buses in the power system;
- $t_c$ is the time of fault clearance, unit: s;
- $U_i$ is the transient voltage of each bus in the power system, units: pu;
- $U_{\text{t,p}}$ is the steady-state voltage of each bus in the power system, unit: pu;

![Figure 1. Diagram of the discretization obtained voltage recovery area $S_i$.](image)

Due to the transient voltage and time characteristic curves of buses are difficult to be expressed by deterministic mathematical formulas, therefore it is necessary to discretize $S$. We divide the 3s into 300 part, each of $\Delta t=0.01$s. Starting with fault remove, the voltage value $U_k (k=1, \ldots, 300)$ is taken at intervals $\Delta t$, use the average of $U_{k-1}$ and $U_k$ to calculate $\Delta S_k$, as show in the following formula:

$$
\Delta S_k = \frac{(U_i - \frac{U_{k-1} + U_k}{2}) \cdot \Delta t}{2} = \frac{(U_i - \frac{U_{k+1} + U_k}{2}) \cdot 0.01}{2}
$$

(3)
The area $S_i$ of bus voltage sags is $S_i = \sum_{k=1}^{300} \Delta S_k$. By discretization, the objective function is transformed into Formula (4).

$$\min S = \sum_{j=1}^{n} S_j = \sum_{j=1}^{n} \int_{t_{j-1}}^{t_j} (U_i - U_{i0}) dt = \sum_{j=1}^{n} \sum_{k=1}^{300} \Delta S_k = \sum_{j=1}^{n} \sum_{k=1}^{300} (U_i - \frac{U_{k+1} + U_k}{2}) \cdot \Delta t$$  \hspace{1cm} (4)

State equation of SVC is as follows Formula (5):

$$B_{CV} = \frac{K_r}{1 + T_r} (U_{ref} - U)$$  \hspace{1cm} (5)

In Formula (5), $U_{ref}$ is the reference voltage amplitude for SVC; $U$ is the actual voltage amplitude for SVC; $K_r$ and $T_r$ are the gain and time constant of the SVC controller, respectively. The SVC bus injection reactive power calculation formula is follows:

$$Q = -B_{CV}U^2$$  \hspace{1cm} (6)

Since SVC installation bus voltage is highly sensitive to compensation capacity, according to Formulas (5) and (6), the mathematical relationship between compensation capacity and bus voltage can be expressed by the following formula:

$$U_{ref} - U = -\frac{Q(1 + T_r) s}{K_r U^2}$$  \hspace{1cm} (7)

After unify the formula (7), combination Formula (4) to (6), the voltage area $S_i$ and compensation capacity of the SVC installed can be expressed in an intuitive mathematical expression, as show in the following formula:

$$S_i = \sum_{k=1}^{300} (-\frac{Q(1 + T_r) s}{K_r U^2 (\frac{U_{k+1} + U_k}{2})^2}) \cdot \Delta t$$  \hspace{1cm} (8)

Assuming that there are $m$ numbers of SVC installed in power system, the objective function Formula (4) can be converted by Formula (9), as show in the following formula:

$$\min S = \sum_{j=1}^{n} S_j = \sum_{j=1}^{n} \int_{t_{j-1}}^{t_j} (U_i - U_{i0}) dt = \sum_{j=1}^{n} \sum_{k=1}^{300} \Delta S_k = \sum_{j=1}^{n} \sum_{k=1}^{300} (U_i - \frac{U_{k+1} + U_k}{2}) \cdot \Delta t$$

$$= \sum_{i=1}^{n} \sum_{k=1}^{300} (-\frac{Q_j(1 + T_{ij} s)}{K_{ij} U_{ij}^2 (\frac{U_{k+1} + U_k}{2})^2}) \cdot \Delta t = \sum_{i=1}^{n} \sum_{k=1}^{300} (U_i - \frac{U_{k+1} + U_k}{2}) \cdot \Delta t$$  \hspace{1cm} (9)

In Formula (9):

- $j=1, 2, ..., n$;
- $Q_j$ is the install capacity for the $j$th bus’s SVC, unit: MVar;
- $K_{ij}$ and $T_{ij}$ are the SVC controller gains and time constants of the $j$th bus’s SVC.
- $U_{ij}$ is the reference voltage for the $j$th SVC bus installation, unit: kV;

Usually, the instability of induction motor load will be obvious on its bus voltage, and its bus voltage will generally drop dramatically to 0.6 pu. Therefore, in this paper, the transient voltage stability constraints are imposed from the perspective of voltage, requiring that the voltage of load buses be restored to more than 0.9 pu within 3s after fault removed. For the constraints of acceptable level of transient voltage sags, according to china’s national standards, requiring that the voltage of load buses be restored to more than 0.75pu within 1s after fault removed [5]. Thus, the constraints are as showing in the follows:
1) In order to ensure the transient voltage stability of power system, it is required that the voltage of each load bus be restored to more than 0.75pu one second after fault removal, which is expressed by mathematical formula.

\[
\begin{cases}
U_{i(t_1+t_\varepsilon)} \geq U_{z1\text{min}} + \varepsilon \\
U_{i(t_1+t_\varepsilon)} \geq U_{z2\text{min}} + \varepsilon
\end{cases}
\]  \hspace{1cm} (10)

Among them: \(U_i\) is the voltage of bus \(i\) under fault; \(t_\varepsilon\) is the time of fault removed, \(t_{z1} = 1s, U_{z1\text{min}} = 0.75\text{pu}, t_{z2} = 3s, U_{z2\text{min}} = 0.9\text{pu}\), advisable \(\varepsilon = 0.01\sim 0.02\).

2) When the power system is gradually restored to steady state after fault removed, the voltage of each bus cannot exceed the upper and lower limit of steady state voltage for normal operation.

\[
U_{\text{wmin}} \leq U_{i(t_\varepsilon+t_\text{w})} \leq U_{\text{wmax}}
\]  \hspace{1cm} (11)

Among them: \(t_\text{w}\) is the time of restoring to steady state after fault clearing, where \(t_\text{w} = 9s; U_{\text{wmin}}\) and \(U_{\text{wmax}}\) are the upper limit of steady state voltage of the system, and \(U_{\text{wmax}} = 1.1\text{p.u.}\; U_{\text{wmin}} = 0.95\text{pu}\).

2.2.2. The second objective function. The second objective function \(J_2\) is defined as the sum of the rated compensation capacity (per unit value) of SVC installed. The objective function \(J_2\) can be set as follows:

\[
\min S = \sum_{i=1}^{m} S_{(\text{SVC})i}
\]  \hspace{1cm} (12)

3. Solving of SVC optimal allocation model

3.1. Crisscross optimization algorithm

Crisscross Optimization Algorithm (CSO) is a new algorithm inspired by Confucianism and genetics. Its search behavior mainly includes two main operators: horizontal crossover and vertical crossover. That is to say, a new compromise particle is generated between two different particles to update the whole population, so as to avoid the PSO algorithm ignoring the horizontal optimal solution and has convergence. It has the characteristics of high accuracy and fast calculation speed, and is especially suitable for solving multi-objective optimization problems [12].

The horizontal crossover of the CSO algorithm is based on the crossover operation between all the dimensions of two particles. The expression is:

\[
\begin{cases}
MS_{hc}(i,d) = r_1 \cdot X(i,d) + (1-r_1) \cdot X(j,d) + c_1 \cdot (X(i,d) - X(j,d)) \\
MS_{hc}(j,d) = r_2 \cdot X(j,d) + (1-r_2) \cdot X(i,d) + c_2 \cdot (X(j,d) - X(i,d))
\end{cases}
\]  \hspace{1cm} (13)

In the Formula (13): \(r_1\) and \(r_2\) are random numbers between \([0, 1]\); \(c_1\) and \(c_2\) are random numbers between \([-1, 1]\). \(X(i,d)\) and \(X(j,d)\) are two different parent solutions; \(MS_{hc}(i,d)\) and \(MS_{hc}(j,d)\) are the offspring of the parent solution after crossover operation.

Vertical crossover of the CSO algorithm is based on the crossover operation between two different dimensions of all particles. Assuming that the \(D_1\) and \(D_2\) dimensions of particle \(X(i)\) are crossed, then:

\[
\begin{cases}
MS_{vc}(i,d_1) = r \cdot X(i,d_1) + (1-r) \cdot X(j,d_2) \\
i \in N(1,M) \\
d_1, d_2 \in N(1,D)
\end{cases}
\]  \hspace{1cm} (14)

In the Formula (14): \(MS_{vc}(i,d)\) is the mean solution of \(X(i,d_1)\) and \(X(i,d_2)\); \(r\) is the random number uniformly distributed in \([0, 1]\); \(M\) is the population size; \(D\) is the total number of particle dimensions.

In each evolutionary iteration, the CSO particles are crossed horizontally and vertically according to Formula (13) and Formula (14) respectively. The solution obtained by crossover operation is called
the moderate solution \((M_{S_{he}}, MS_{he})\); the moderate solution competes with its parent particles according to the competition strategy, and the fitness of the best survives. The solution obtained by competition is called the dominant solution \((DS_{he}, DS_{he})\). The moderate solution \(MS_{he}\) produced by horizontal crossover competes with the dominant solution \(DS_{he}\) produced by vertical crossover, and the moderate solution \(MS_{he}\) produced by vertical crossover competes with the dominant solution \(DS_{he}\) produced by horizontal crossover, and so on. In the new generation of individuals, only particles with better fitness than their parents survive, while other particles are eliminated in the competition. This competition mechanism ensures that the crossover search is always maintained in the historically optimal population, thus increasing the accuracy of the solution and accelerating the convergence rate.

In this paper, CSO algorithm is used to solve multi-objective SVC optimal allocation problem. In solving the problem, each CSO particle represents a potential solution, and the expression of the particle is shown in Equation (15).

\[
X_i = [S_{(svc)1}, S_{(svc)2}, ..., S_{(svc)m}]
\]

Formula (15): \(S_{(svc)1}, S_{(svc)2}, ..., S_{(svc)m}\) is the installation capacity of SVC; \(m\) is the number of installation location of SVC.

3.2. Optimal SVC capacity by crisscross optimization algorithm

1) Input the basic data of power grid, make time-domain transient simulation of the power system, and determine the critical fault sets \(\{F_1, F_2, ..., F_N\}\) which threaten the transient voltage stability of the power system, and according to the voltage recovery level of each bus during the fault period, preliminary determination of the selected SVC installation bus \(\{1, 2, ..., m\}\).

2) SVC is installed on each bus to be selected, and time domain transient simulation of key faults is carried out again.

3) From the first two steps of time domain transient simulation results, the TSI of bus \(j (j=1, 2, ..., m)\) is calculated according to Reference [6].

4) According to TSI, the selected buses are sorted, and the maximum index value is the optimal buses for SVC installation

5) CSO population size \(N_{pop}\), maximum iteration number MaxIter, sampling size \(N_s\) and other parameters are set to initialize the CSO population and generate the initial configuration capacity of SVC.

6) The implicit trapezoidal integration method is used to calculate the time domain transient simulation, and the objective function and fitness are calculated by the transient calculation results to check whether the constraints are satisfied. If satisfied, proceed to the next step; otherwise, add penalties to the fitness of the particle and proceed to step 7.

7) Save the current particle optimal value \(g_{best}\) and determine whether the end condition is satisfied. If so, output the optimal value \(g_{best}\) as the optimal configuration scheme, otherwise proceed to step 8.

8) According to Formulas (13) and (14), CSO populations are crossed horizontally and vertically, and new populations are generated through competition between offspring and parents.

9) Back to step 6, the implicit trapezoidal integral method is used to re-calculate the transient state and the objective function value of the new population. The optimal SVC configuration capacity is output until step 7 satisfies the end condition, and the global optimal solution based on CSO algorithm is the optimal installation location and capacity of SVC.

4. Analysis of examples

In this paper, the time domain transient simulation of IEEE39 bus system is to further illustrate the rationality and effectiveness of the above optimization algorithm. IEEE39-bus system diagram is shown in Figure 2. The bases capacity of IEEE39 bus system is 100 MVA. All loads of the system are equipped with 60% induction motor and 40% constant impedance load ratio. The parameters of induction motor load model are calculated in Table 1.
**Figure 2.** IEEE39-bus system diagram.

**Table 1.** Induction motor parameters.

| IM Parameters | $R_s$ | $X_s$ | $X_m$ | $R_r$ | $X_r$ | $A$ | $B$ | $H$ | $K_L$ |
|---------------|-------|-------|-------|-------|-------|-----|-----|-----|-------|
| Parameter’s value | 0.077 | 0.107 | 2.22  | 0.079 | 0.098 | 1.0 | 0   | 0.74 | 0.46  |

**Table 2.** IEEE39-bus system faults of filtering and sorting results.

| Fault   | $PI$  | rank | Fault  | $PI$  | rank |
|---------|-------|------|--------|-------|------|
| L16-17  | 2.431 | 1    | L7-8   | 6.348 | 6    |
| L21-22  | 3.127 | 2    | L5-6   | 6.816 | 7    |
| L2-25   | 4.351 | 3    | L21-22 | 7.538 | 8    |
| L6-11   | 4.978 | 4    | L28-29 | 7.657 | 9    |
| L5-8    | 5.376 | 5    | L10-13 | 8.353 | 10   |

The fault screening and sequencing results of IEEE39 bus system are shown in Table 2 by referring to the voltage forecasting fault screening and sequencing algorithm in Reference [11], which takes into account transient voltage stability.

When three-phase grounding short-circuit fault occurs in line BUS16-17 of IEEE39 bus system, the transient voltage of the system loses stability quickly and has great influence. After the fault clearance, the BUS16-17 line is disconnected, the power flow of the system shifts in a large range, the direct electrical connection between the systems is lost, and the electrical connection between the systems becomes weaker. Therefore, the three-phase metal grounding short-circuit fault of the BUS16-17 line is the single fault that has the greatest impact on the system. Therefore, considering the fault form, the time-domain transient simulation calculation time of the system is 10 s, the three-phase short-circuit fault occurs when $t = 1$ s, and the fault clearance when $t = 1.1$ s.
When SVC is not installed, the above fault will lead to transient voltage instability of the system, as shown in Figure 3 and Figure 4. For this fault form, the voltage-reactive sensitivity index TSI of the actual SVC model is calculated according to Reference [11], the bus which is sensitive to reactive power change is selected to install SVC among all buses of the system. In this paper, the installation location of SVC is selected as 8, 15, 18, 24 and 28 buses.

CSO algorithm is used to optimize the SVC capacity. The number of particles is n=10 and the number of iterations is m=200. The fitness curve of the objective function with the number of iterations is shown in Figure 5. The optimized SVC capacities installed at bus 8, 15, 18, 24 and 28 are 81.9 MVar, 59.1 MVar, 6.3 MVar, 109.3 MVar and 110.8 MVar, respectively. The voltage variation during the installation of SVC under system fault is investigated, as shown in Figures 6-7. As can be seen from Figures 6-7, the system voltage can remain stable after installing SVC.

![Figure 3. Voltage curves under the specified fault when not allocation SVC.](image1)

![Figure 4. Induction motor’s slip curves under the specified fault when not allocation SVC.](image2)
5. Conclusions

In this paper, an optimal configuration scheme of SVC installation location and capacity considering the safety of transient voltage is proposed. Taking into account the dynamic characteristics of induction motor load, the voltage sensitive bus of the system is determined by calculating the trajectory sensitivity, and the optimal installation location of SVC is determined by considering the reactive power balance in the system area. CSO algorithm is used to optimize the SVC capacity of bus installation, so as to solve the optimal capacity of SVC. The scheme makes full use of the fast and controllable characteristics of SVC to provide dynamic support for load bus voltage of power system after fault, so that the system meets the requirements of transient voltage safety. Through the simulation of IEEE39-bus system, it is proved that SVC can restore the transient voltage security of the system with transient voltage instability, and the rationality and validity of the scheme are verified.
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