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Multi-objective optimization evaluation method based on coordination control algorithm for magnetic energy recovery switch

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Abstract: The Magnetic Energy Recovery Switch is a kind of novel reactive power compensation device which supplies continuous reactive power. In this paper, the conventional control method of the Magnetic Energy Recovery Switch is introduced, and then the coordination algorithm based on phase delay control and minimum capacitor voltage control is analyzed emphatically. The Magnetic Energy Recovery Switch working curve is obtained under the premise of reaching required reactive power in the grid. And then for the all operating points in the curve have been assessed to find the optimal operating point of Magnetic Energy Recovery Switch. Finally, a simulation is conducted to verify the effectiveness and rapid dynamic performance of the evaluation method.

1. Introduction

With the advent of new power electronic devices, especially in recent years, the rapid development of full-controlled devices such as gate turn-off thyristor (GTO) and insulated gate bipolar transistor (IGBT) etc., promoting the diversification of reactive power compensation technology development, and thus derived a series of new reactive power compensation devices such as static synchronous series compensator (SSSC), gate converter series capacitor (GCSC) and so on. The static synchronous compensator (STATCOM) based on voltage source converter (VSC) is the fastest developedparalleled reactive power compensation device in recent years [1-5]. Compared with reactive power compensator controlled by thyristor, STATCOM generally uses high-frequency switching control, with the characteristics of high compensation precision, fast response, and direct reactive power generation [6-8]. Also, due to the use of full-controlled semiconductor devices to make its high quality harmonic performance [9-12].

The Magnetic Energy Recovery Switch (MERS) is a compensator based on single-phase VSC, which is controlled by grid frequency [8-10]. Compared with other voltage compensators such as SSSC, it has the advantages of smaller fixed capacitor in VSC circuit. However, the shortcomings of the Magnetic Energy Recovery Switch are also obvious: When it is used, the current harmonic which is injected into the grid is relatively large, the DC side of the capacitor voltage is easy to steep rise, threatening the safety of the operating environment. To solve the problems and shortcomings up above, this paper proposed a multi-objective optimization evaluation method based on coordinated control algorithm of Magnetic Energy Recovery Switch. Through the cooperative control of the traditional phase delay and the minimum voltage of the capacitor, the equal power curve of the Magnetic Energy Recovery Switch is obtained under the premise that the reactive power compensation power of the
grid is reached[13-14]. On the basis of this, all the operating point on the equal power curve are evaluated according to the objective function that acquired from evaluation model proposed in this paper, and finally the optimal operating point satisfying the reactive power compensation is obtained.

2. Circuit configuration and schematic of magnetic energy recovery switch
Magnetic Energy Recovery Switch(MERS) topology is shown in Figure1. Vertical pairs switches T1 ~ T4 (including its reverse-parallel diodes D1 ~D4) and DC capacitor Xdc, semiconductor switches are insulated gate bipolar transistor (referred to as IGBT), Tx and Dx (x = 1~4) complemenal paralleled each other conventionally , The left and the right pairs of switches are connected in series to form two arms, the bridge arm and the DC side capacitor XC are connected in parallel, where point a and b are connected with the live line L and neutral line N of the single phase power grid respectively, also a current limiting inductor XL is connected in circuit to prevent current shaking.

**Table 1.** Magnetic energy recovery switch mode.

|                | T1 | T2 | T3 | T4 |
|----------------|----|----|----|----|
| Double tube    | ON | OFF| ON | OFF|
| Turning-on     | OFF| ON | OFF| ON |
| Single tube    | OFF| ON | OFF| OFF|
| Turning-on     | OFF| OFF| ON | OFF|

The upper and lower switches of the same arm are controlled by complemenal switching signals, which means that in addition to the dead time, switches of the same arm cannot be both ON and not more than two of the four IGBT can be ON at the same time. By controlling the two pairs of switches, different combination results could be obtained according to its switch state, as shown in Table 1.

Figure.2.has showed the current loop under condition of double tube turning on. Figure.2. (a)-(e) is the configuration of fixed capacitor in series into the AC bus; Figure(c), Figure (f) are the configuration of double-tube bypass mode, under this very condition fixed capacitor voltage drops to zero, and capacitor does not inject any power to the AC bus.

**Figure 2.** Current paths of the magnetic energy recovery switch under operating condition.

Figure.3. shows the MERS single bypass mode current path diagram, each kind of current outflow direction has two paths to choose from, at this time, capacitor does not inject any power to the AC bus,
the working situation is just similar with double-tube turning on mode. When in actual control, the two paths will conduct in turn to bring down the calorific value.

Figure 3. Current paths of the magnetic energy recovery switch under single bypass mode.

Figure 4. Circuit diagram of direct phase delay control

3. Control strategy of magnetic energy recovery switch

3.1. Direct phase delay control

Circuit diagram of the Direct Phase Delay Control (DPDC) of the MERS is shown as Figure 4. The phase of the AC bus as a reference can be traced by the phase-locked loop technique, then adjusting the trigger hysteresis to control the output of the compensated reactive power. In Figure 4, \( \pi \) is the conduction pulse width, which is the delay trigger pulse angle. GT1, GT3 and GT2, GT4 are two pairs of complementary conduction IGBT turn-on switch signals.

Figure 5. Circuit diagram of direct phase delay control.

DPDC simulation waveform of MERS with PSIM software is shown in Figure 5. \( \alpha \) values 20 degrees, the Us represents the voltage of grid, Umers, Uc represents MERS voltage and the fixed capacitor voltage in the circuit respectively. Figure 6. shows the reactive power compensation characteristic of MERS. It can be seen that the output of reactive power, current total distortion rate (THD) and capacitance peak voltage soars with the increase of the \( \alpha \). Also, the peak voltage of the capacitor grows slowly at the beginning, and finally increases exponentially. The total distortion rate (excluding the triple harmonic) has a process of rapid increase and then a slight decrease. Therefore, if improving the reactive power output of the Magnetic Energy Recovery Switch is wanted, merely increasing in the trigger delay angle will cause the total distortion of the current (excluding the triple harmonic) and fixed capacitor peak voltage bounce, which will eventually affect the selection range of the operating point and results in the limited reactive power adjustment range.
3.2 Minimum voltage control of capacitor

Figure 7. shows the circuit diagram of the minimum voltage control of capacitor (MVCC). In the Magnetic Energy Recovery Switch, the fixed capacitor in the circuit plays a role in storing energy. Some control methods have been taken to make sure that the capacitor discharge is not complete to zero but still saves a certain amount of electricity when operating, thus corresponds to increasing the equivalent capacitance of the capacitor, can expand the ranges of reactive power compensation adjustment. There are two primary ways to achieve the minimum voltage control of the capacitor: changing the early turn-off angle and controlling capacitor minimum voltage $V_c$ directly. Generally, the control characteristics obtained by directly controlling the minimum voltage of the capacitor is better, because the capacitor voltage value can be detected directly, while changing the early turn-off angle may exist a secondary error. It can be seen from Figure 8 that the MVCC can achieve a better operating characteristic of voltage and current.

As can be seen in Figure 9, the output reactive power of the MERS decreases as $V_c$ increases, but it is noteworthy that the capacitor voltage also has the same tendency to change. The total current distortion rate decreases at the beginning then increases rapidly as $V_c$ increases.

Figure 6. Direct phase delay control waveforms of MERS.

Figure 7. Reactive compensation characteristics with DPDC.

Figure 8. Circuit diagram of minimum voltage control of capacitor.
Figure 9. Minimum voltage control of capacitor waveforms of MERS.

Figure 10. Reactive compensation characteristics with MVCC.

In summary, increasing the delay trigger angle $\alpha$ increases the output reactive power of MERS, but the fixed capacitor voltage and current total distortion rate increase as well; increasing $V_{c-min}$ can reduce the capacitive reactive power output, achieving the goal of capacitor voltage peak adjustment, then the current harmonics would have a process of increasing rapidly at the beginning then decreasing gradually. In actual operation, the reactive power output range of the MERS is mainly affected by the current harmonics and the capacitor voltage. The current harmonics make the lower limit of the reactive power compensation boundary rises, and the capacitance withstand voltage causes the upper limit down, resulting in its adjustable range narrowing.

To restrain current harmonics and peak voltage of capacitor concurrently a novel kind of Multi-Objective Optimization Evaluation Method Based on Magnetic Energy Recovery Switch Coordinated Control Algorithm is proposed. A considerably wide range of parameters $V_{c-min}$ and $\alpha$ should be coordinated when meeting the power quality requirements in the grid. By establishing a coordination control and evaluation model, the proposed control algorithm realizes a better working performance compared to conventional control strategy. Meanwhile, the optimal operating point is attained.

4. Multi-objective optimization evaluation method based on coordination control algorithm

4.1. Principle of regulation
As shown in Figure 10. is Coordinated control circuit diagram of MERS. The first floor is directly phase-delay control. For providing reference phase the phase-locked loop is added, aiming to control IGBT T1,3 T2,4 conduct for half cycle in turn. T1,3 lags behind synchronous phase $\alpha$ degree, T2,4 lags 180 degree based on the T1,3.

Added to the basis of Directly Phase-Delay Control is the Minimum Voltage Control of Capacitor. This paper checks capacitor voltage $V_c$ in the phase interval $[0.5\pi, 1.5\pi]$, when the voltage of
capacitor lower than the settled threshold $V_{c-min}$, T3 will turn off to bypass the fixed capacitor in advance. In this coordination algorithm, the control of $V_{c-min}$ and $\alpha$ is independent respectively and does not interfere with each other. Therefore, these two variables could be controlled at the same time. During the overall operation, Control of $\alpha$ increases reactive power output, while $V_{c-min}$ suppresses harmonics and peak capacitor voltage. The purpose of coordinated control is to find the optimal operating point of the MERS in the process of reactive power compensation, broaden its reactive power compensation range, and reduce the total current distortion rate (THD) and the capacitor voltage in the circuit.

\[ Q(\alpha, V_{c-min}) = \sum_{i=1}^{A} x_i \alpha^i + \sum_{j=1}^{B} y_j V_{c-min}^j + \sum_{k=1}^{C} z_k \alpha^j V_{c-min}^k + C_Q \]  
\[ V_{peak}(\alpha, V_{c-min}) = \sum_{i=1}^{A} x_i \alpha^i + \sum_{j=1}^{B} y_j V_{c-min}^j + \sum_{k=1}^{C} z_k \alpha^j V_{c-min}^k + C_V \]

**Figure 11.** Coordinated control circuit diagram of MERS.

**4.2. Multi-objective optimization evaluation method**
Using the control model and run the test several times then plot the simulation data to the working surface shown in Figure 11. The output of MERS reactive power, peak capacitor voltage and the total current distortion rate with the trigger delay angle $\alpha$ and $V_{c-min}$ changes could be observed vividly.

**Figure 12.** Curve surface of coordinated algorithm.

**4.3. Multiple regression analysis**
As shown in Figure 12., a curve surface on the basis of the simulation results is derived. The figure describes the outputting reactive power, peak capacitor voltage and total current distortion rate respectively. The variables in vertical axis are all multivariable functions of $\alpha$ and $V_{c-min}$. Changing regularities can be represented with formula (1) to (3)
\[ THD(\alpha, V_{c-min}) = \begin{cases} \sum_{i=1}^{A} x_i \alpha_i + \sum_{i=1}^{B} y_i V_{c-min}^i + \sum_{i=1}^{A} \sum_{j=1}^{B} z_{ij} \alpha_i V_{c-min}^j + C_{THD1}, & \text{when } \alpha \leq \varepsilon \\ \sum_{i=1}^{A} x_i \alpha_i + \sum_{i=1}^{B} y_i V_{c-min}^i + \sum_{i=1}^{A} \sum_{j=1}^{B} z_{ij} \alpha_i V_{c-min}^j + C_{THD2}, & \text{when } \alpha > \varepsilon \end{cases} \] (3)

\( x_i, y_i, z_{ij} \) denotes unknown variables which are called regression coefficients; \( A \) is the possible highest power. Error terms \( CQ, C_{v}, C_{THD1}, C_{THD2} \) denote unobservable random variables with means of zero and variances \( \delta > 0 \). Assume that \( C_{Q,V,THD,THD} \sim N(0, \delta) \), this model is known as multiple regression model, \( Q(\alpha, V_{c-min}), V_{peak}(\alpha, V_{c-min}), THD(\alpha, V_{c-min}) \) are dependent variables of prediction model, while \( \sum_{i=1}^{A} \alpha_i, \sum_{i=1}^{B} V_{c-min}^i \) are arguments. Observe from Figure.11(c), \( THD(\alpha, V_{c-min}) \) occurs an obvious chattering phenomenon at \( \alpha = 25^\circ \), so \( \varepsilon = 25^\circ \) and construct a piecewise function will maximally increase the accuracy of fitting.

The regression coefficients are used in the least-square-method to change \( A \) and fitting repeatedly to choose the maximum of Multiple Correlation Coefficient \( R \). Relationship between arguments and dependent variables can be seen as closer with larger \( R \), the largest \( R \) corresponds to the most suitable power \( A \).

4.4. Dynamic weighted round-robin

Due to the evaluation system involves two physical quantities: peak of capacitor voltage and total current distortion rate. Cannot unify order of magnitude and dimension of numerical values, it is obviously illogically to use constant weight method. Hence, this paper chooses dynamic weighted round-robin for object functions evaluation system.

For each evaluate index, construct three-grade evaluation criterion, the numerical values in the table are percentage of evaluation objects input upper limits. As shown in table 2.

| Tab 2. Evaluation criterion. |
|-----------------------------|
| Evaluate objects | Evaluate range |
|-------------------|----------------|
| Peak of capacitor voltage | Grade I | Grade II | Grade III |
| (0,30%) | (30%,60%) | (60%,100%) |
| THD | (0,40%) | (40%,80%) | (80%,100%) |

According to the reality of evaluation, the influences of indexes to the final fitted number satisfy a characteristic which increase slowly firstly, grow rapidly in the middle time then trend gently to the maximum. Considering that, partial normal distribution function is selected as dynamic weighted function, that is:

\[ \omega_i(x) = \begin{cases} 0, & \text{when } x < \beta_i \\ 1 - e^{-\left(\frac{x-\beta_i}{\alpha_i}\right)^2}, & \text{when } x > \beta_i \end{cases} \] (4)

\( \beta_i \) is the median of the first grade evaluate standard interval of index \( x_i \), \( \sigma_i \) is determined by

\[ \sigma_i = x - \frac{\beta_i}{\sqrt{-\log 0.1}} \] (5)

4.5 Multi-objective evaluation method modeling

To control the peak of capacitor voltage and total current distortion rate at the same time, an objective function based on the purpose of obtaining minimum of the two indexes is presented. The constraint
conditions should satisfy the upper limits of the two indexes and function relationship fitted with evaluation function. The specific expressions are as follows:

\[
\begin{align*}
\min \text{FIT} &= \omega_1 f_{v_{\text{peak}}} (\alpha, V_{c-min}) + \omega_2 f_{\text{THD}} (\alpha, V_{c-min}) \\
& \begin{cases} \frac{f_{\text{THD}} (\alpha, V_{c-min})}{\eta \text{THD}(\alpha, V_{c-min})} & \text{when } f_{v_{\text{peak}}} (\alpha, V_{c-min}) \leq \beta_{v_{\text{peak}}} \\
1 - \left( \frac{f_{v_{\text{peak}}} (\alpha, V_{c-min}) - \beta_{v_{\text{peak}}}}{\sigma_{v_{\text{peak}}}} \right)^2 & \text{when } f_{v_{\text{peak}}} (\alpha, V_{c-min}) > \beta_{v_{\text{peak}}} \end{cases} \\
& \begin{cases} 0, & \text{when } f_{\text{THD}} (\alpha, V_{c-min}) \leq \beta_{\text{THD}} \\
1 - \left( \frac{f_{\text{THD}} (\alpha, V_{c-min}) - \beta_{\text{THD}}}{\sigma_{\text{THD}}} \right)^2 & \text{when } f_{\text{THD}} (\alpha, V_{c-min}) > \beta_{\text{THD}} \end{cases} \\
0 \leq V_{\text{peak}} (\alpha, V_{c-min}) \leq V_{\text{peak, max}} \\
0 \leq \text{THD}(\alpha, V_{c-min}) \leq \text{THD}_{\text{max}} \end{align*}
\]

\( \omega_1, \omega_2 \) are weight coefficients; \( f_{v_{\text{peak}}} (\alpha, V_{c-min}) \) is the peak of capacitor voltage evaluation function; while \( f_{\text{THD}} (\alpha, V_{c-min}) \) is the total current distortion rate evaluation function. Evaluate functions have the ability to do non-dimensional treatment for the two indexes, preventing small number from being ignored due to the effect of big number. \( \eta \) is the proportional coefficient; \( V_{\text{peak}} (\alpha, V_{c-min}) \), \( \text{THD}(\alpha, V_{c-min}) \) are the number of peak of capacitor voltage and total current distortion rate separately; \( V_{\text{peak, max}} \), \( V_{\text{peak, min}} \), \( \text{THD}_{\text{max}} \), \( \text{THD}_{\text{min}} \) are upper and lower limits respectively.

5. Sample analysis
To verify the validity of above method, this paper uses the output reactive power 1000 \( V_{\text{qr}} \) as a sample to solve the optimal operating point of the Magnetic Energy Recovery Switch. The coefficients in equation (3) can be fitted according to the method described in section 4 as shown in table 3.

Reactive power 1000 \( V_{\text{qr}} \) is inputted as requirement to the first group of functions in table 3 to obtain a set of equal reactive power outputs. Each set of outputs composes of two-dimensional operating point \( (\alpha, V-c_{\text{min}}) \), setting 0.1 as the minimum steps of the two-dimensional variables, outputs shown in table 4.

In table 4 all the operating points constitute a two-dimensional working curve, every set of outputs which corresponds to the curve satisfies the requirement of input reactive power 1000 \( V_{\text{qr}} \). Further fitness evaluations aimed at all operating points in table 4 are required to find the optimum point which satisfies the minimum peak of capacitor voltage and total current distortion rate simultaneously.

Plugging all the operating points into the multivariate nonlinear regression functions in the second third and fourth rows, the 12 sets of peaks of capacitor voltage and total current distortion rate obtained can be sorted by fitness according to equation (5) and (6). Finally, the two-dimensional operating point corresponded to the minimum fitness is selected as the optimum. From the result of fitness order in table 5 and Figure.13 , (35.2, 35.7) can be known as the optimum point. Operating performance can be improved when magnetic recovery switch works at the optimum point considering the minimum peak of capacitor voltage and the minimum total current distortion rate are alleviated.
Table 3. Multiple regression coefficients.

| Equations          | The Highest Power | Constant Term | $\alpha^2$ | $\alpha$ | $V_{c_{-\text{min}}}$ | $V_{c_{-\text{min}}}$ | $\alpha*V_{c_{-\text{min}}}$ |
|--------------------|-------------------|---------------|------------|----------|----------------------|----------------------|---------------------------|
| $Q(\alpha,V_{c_{-\text{min}}})$ | 2                  | 606.723       | 2.2442     | 62.3029  | -0.0117              | 0.2839               | -0.1508                    |
| $V_{\text{peak}}(\alpha,V_{c_{-\text{min}}})$ | 2                  | 617.7193      | 0.9576     | -        | -0.0001              | 1.6715               | -0.1078                    |
| $THD_1(\alpha,V_{c_{-\text{min}}})$ | 2                  | 7.4641        | 0.0245     | -0.7138  | -0.0003              | 0.0989               | 0.0066                     |
| $THD_2(\alpha,V_{c_{-\text{min}}})$ | 2                  | -0.1501       | 0.0069     | 0.4555   | 0.0001               | -0.05                | 0.001                      |

Table 4. Equal reactive power outputs.

| $\alpha$ | 33.2 | 33.3 | 34.1 | 34.3 | 35 | 35.2 | 36.1 | 38.1 | 38.5 | 39.9 | 40.9 | 42.5 |
|-----------|------|------|------|------|----|------|------|------|------|------|------|------|
| $V_{c_{-\text{min}}}$ | 2.5  | 4.3  | 18.1 | 21.4 | 32.6 | 35.7 | 49.2 | 77.1 | 82.4 | 100.4 | 112.8 | 132  |

Table 5. Fitness ranks.

| Operating points | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|------------------|---|---|---|---|---|---|---|---|---|----|----|----|
| Value            | 0.447 | 0.436 | 0.3752 | 0.3688 | 0.3498 | 0.3490 | 0.3620 | 0.4638 | 0.4937 | 0.6136 | 0.7123 | 0.8869 |

Figure 13. Bar graph of fitness.

The simulation model is set up to demonstrate the validation of proposed algorithm. Operation points (34.3,24.1) and (35.2,35.7) are both equivalent reactive power points of 1000Var. (35.2,35.7) is the optimal operating point obtained by using the multi-objective optimization algorithm proposed in this paper. (34.3,24.1) represents non-optimal operating points in equivalent reactive power curve. Waveform comparison between (34.3,24.1) and (35.2,35.7) are shown as Figure 14. It is obviously that under optimum operating condition the voltage amplitude and triple or more harmonic rate of MERS are lower than non-optimal operating point which means the goal of proposed algorithm has attained.

Figure 15 shows the dynamic response of the load switching. The first switching occurs at 1.12s, The grid power factor drops immediately and reverts to a unit after 0.06s. The second load change at
1.3s, and the recovery takes about 0.06s. The first part of Figure 15 shows changes in grid power, the waveforms of voltage and current are shown in the below.

Adopting the evaluation algorithm proposed in this paper, The MERS works as a compensator to track the reactive power in the grid. The feasibility and rapid dynamic performance are finally verified.

**Figure 14.** Waveform comparison when MERS generate same reactive power.

**Figure 15.** Dynamic characteristics of MERS.

### 6. Conclusions

Magnetic Energy Recovery Switch as a novel reactive power compensator is investigated. Several works have been done as following. Firstly, the conventional phase delay control and minimum voltage control of the capacitor for Magnetic Energy Recovery Switch are introduced. Secondly, the feasibility and superiority of the parameter coordination control are clarified. And the coordinated control of the Magnetic Energy Recovery Switch is analyzed in detail. Thirdly, the multi-objective optimization evaluation method based on the coordinated control algorithm of Magnetic Energy Recovery Switch is proposed. The method finds the optimal operating point of the MERS based on the target for retraining current harmonics and peak voltage of the capacitors. Finally, a simulation is set up to validate that the proposed method is effective and has the performance of fast dynamic response.
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