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Study on Optimization Design Method of Energy Storage Device for Dynamic Voltage Restorer Based on Ultra-Capacitor

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Abstract. Ultra-capacitor is ideal for use as energy storage device for active distribution network, for instance, in the field of electric vehicle, uninterrupted power supply and dynamic voltage restorer, etc. When the bus voltage rises, the number of ultra-capacitor units increases, which in turn leads to higher costs. Changing the ratio of series-coupled transformer can reduce the injection voltage of the inverter and then reduce the bus voltage, which means that the number of ultra-capacitor units decreases. However, the ultra-capacitor discharge current will increase, which leads to higher withstand current of switching device. The design of transformation ratio need to be carefully considered. In this paper, with the relationship between the transformation ratio and the number of units deduced from the energy formula and the power formula of ultra-capacitor discharging, it is easy to find an appropriate transformation ratio to achieve the optimal performance. The feasibility of the design method is validated by the experimental results with a 200kVA DVR device.

1. Introduction
In active distribution network, dynamic voltage restorer (DVR), as a power quality control device, can effectively suppress voltage sags and ensure the normal operation of sensitive loads such as automatic control equipment, computer and precision instruments[1-3]. In order to achieve effective compensation, DVR needs to inject active power and supply energy from energy storage device. Typical and potential energy storage devices include batteries, ultra-capacitors, superconducting energy storage and flywheel energy storage. As a highly polluting and inefficient energy storage device, battery has been phased out gradually. Some manufacturers have provided flywheel energy storage products in the areas of uninterrupted power supply, wind power generation and so on, but new composite materials with high energy density are needed and the use cost is relatively high [4]. The superconducting energy storage is still in the research stage, and the real industrialization [5] has not yet been realized. Ultra-capacitor technology has high power density, long cycle life, fast charge and discharge speed, so many manufacturers can provide mature products [6-8]. Therefore, the choice of ultra-capacitor as an energy storage device for DVR is an advantage.

In general, the bus voltage determines the number of ultra-capacitor units in series and the cost of energy storage device. Changing the ratio of series coupling transformer can change the injection
voltage of inverter, which means that the bus voltage can be changed[9]. Therefore, how to design variable ratio to optimize the performance and cost of energy storage devices becomes a key issue. From the point of view of energy and power requirements of energy storage devices, this paper deduces the mathematical relationship between the number of ultra-capacitor units and the ratio of transformer. Considering the limitation of the characteristics of switching devices and capacitors, the variable range of the ratio is further determined. Finally, the energy storage device with high performance is designed by choosing an appropriate variable ratio. A 0.4kV 200kVA DVR system is designed to verify the proposed design method.

2. Design of ultra-capacitor module

![Figure 1. The schematic diagram of DVR device.](image)

In this paper, the ultra-capacitor module is used as the energy storage device of DVR, and the schematic diagram of DVR device is shown in Figure 1. Generally speaking, the ultra-capacitor module is composed of several units in series. Therefore, the maximum withstand voltage, capacitance and series equivalent resistance of ultra-capacitor module are respectively given as

\[ U_{dc_{\text{max}}} = N_p \times U_p \]  
\[ C = \frac{C_p}{N_p} \]  
\[ R_{eq} = N_p \times R_p \]

where, \( N_p \) is the number of unit, \( U_p \) is the voltage amplitude of unit, \( C_p \) is the capacitance of unit, and \( R_p \) is the series equivalent resistance of unit. In order to retain a certain margin, the bus voltage is calculated as

\[ U_{dc} = M_1 \times U_{dc_{\text{max}}} \]  

where, \( M_1 \) is chosen as 0.9 in this study.

The voltage drop on the series resistors of the ultra-capacitor module can not be neglected when discharging. Hence, the expression of the bus voltage in the discharging cycle is shown as

\[ U_{dc_{\text{out}}} = U_{dc} - R_{eq} \times I_{dc} \]

where, \( I_{dc} \) is the rms value of discharging current. By substituting (1)-(4) into (5), the bus voltage in the discharging cycle which can be accommodated is

\[ U_{dc_{\text{out}}} = M_1 \times N_p \times U_p \times N_p \times R_p \times I_{dc} \]

In order to avoid over-modulation, the minimum value of bus voltage needs to satisfy the following relation,

\[ U_{dc_{\text{min}}} = \sqrt{2} \times U_{o_{\text{max}}}/M_2 \]

where, \( U_{o_{\text{max}}} \) is the maximum rms value of injection voltage of DVR, and \( M_2 \) is the maximum modulation index\((M_2=0.85)\). The ratio of series coupling transformer is \( N_{st}:1 \),

\[ U_{o_{\text{max}}} = U_{d_{\text{max}}}/N_{st} \]

By substituting (8) into (7), the expression can be given as

\[ U_{dc_{\text{min}}} = \sqrt{2} \times U_{d_{\text{max}}}/(M_2 \times N_{st}) \]
In general, DVR will have two design index, one is rated power, the other is the compensation time, that is, to meet the requirements of power and energy injection. According to the discharge characteristics of capacitors, the following equations are obtained as

\[
\left(\frac{1}{2}CU_{dc\_out}^2 - \frac{1}{2}CU_{dc\_min}^2\right) \geq \frac{U_{d\_max}}{U_{rated}} PT
\]

\[
C\left(U_{dc\_out} - U_{dc\_min}\right) \geq \frac{I_{dc\_max}}{T}
\]

where, \(U_{rated}\) is rms value of rated load voltage, \(P\) is rated active power of load, \(T\) is compensation time.

On the basis of the discharge characteristics of capacitors, the discharge current will increase gradually. When the bus voltage reaches the minimum, the discharge current is the largest. Therefore, in order to simplify the analysis process, the discharge current takes the maximum value, that is,

\[
I_{dc} = I_{dc\_max} = \frac{U_{d\_max}}{U_{rated}} * \frac{P}{U_{dc\_min}} = \frac{M_2 N_p P}{\sqrt{2U_{rated}}}
\]

According to the constraint of energy and power, the formula for calculating the number of ultra-capacitor units can be obtained.

(1) Energy constraint

By substituting (6,9,12) into (10), the equation can be given as

\[
N_p^2 \left( M_2 U_p - \frac{N_p M_p R_p P}{\sqrt{2U_{rated}}} \right)^2 - N_p \frac{2PTU_{d\_max}}{C_p U_{rated}} \frac{\left( \frac{2U_{d\_max}}{N_p M_2} \right)^2}{\geq 0}
\]

Solve the upper equation, the number of ultra-capacitor units is calculated as

\[
N_p \geq \sqrt{ \frac{PTU_{d\_max}}{C_p U_{rated}}} \geq \frac{\left( \frac{PTU_{d\_max}}{C_p U_{rated}} \right)^2}{\left( M_2 U_p - \frac{N_p M_p R_p P}{\sqrt{2U_{rated}}} \right)^2 + \frac{\left( \frac{2U_{d\_max}}{N_p M_2} \right)^2}{\left( M_2 U_p - \frac{N_p M_p R_p P}{\sqrt{2U_{rated}}} \right)^2}}
\]

(2) Power constraint

By substituting (6,9,12) into (11), the equation can be derived as

\[
M_2 U_p - \frac{\sqrt{2U_{d\_max}}}{N_p N_r M_1} \geq \frac{N_p M_p P}{\sqrt{2U_{rated}}}
\]

Solve the upper equation, the number of ultra-capacitor units is calculated as

\[
N_p \geq \sqrt{ \frac{U_{d\_max}}{2} - \frac{N_p^2 M_p^2 P}{\sqrt{2U_{rated}}} \frac{T}{C_p + R_p}}
\]

Figure 2 shows the relationship between \(N_p\) and \(N_{st}\). Curve 1 is drawn by equation(14), while curve 2 is drawn by equation(16). In order to satisfy the two requirements at the same time, the curve of larger \(N_p\) should be considered in the analysis process. When \(N_{st}\) increases and the discharge current exceeds \(M_2 U_p/(T/C_p+R_p)\), the \(N_p\) in curve 2 becomes negative, which is similar to the spillover phenomenon. Compared with the energy constraint, the power constraint is more sensitive to the change of current. Therefore, the relationship between \(N_p\) and \(N_{st}\) can be analyzed only according to the power constraint. After the design is completed, the parameters can be substituted into the equation(14) to verify whether the energy injection meets the requirements.
3. Variation range of the ratio of series coupling transformer

The variation range of $N_{st}$ is influenced by two factors, one is the constraint of IGBT characteristics and the other is the constraint of capacitor characteristics.

3.1. The constraint of IGBT characteristics

For the reason that the rated voltage and current of IGBT will limit the discharge current and bus voltage, the range of variation of $N_{st}$ will be further narrowed. Assuming that the maximum rated current of an alternative IGBT is $I_{c\text{-max}}$, the equation is given as

$$N_{st} \leq 3 \cdot M_3 \cdot \frac{U_{\text{rated}} \cdot I_{c\text{-max}}}{P}$$

(17)

where $M_3 = 0.5$. Assuming that the maximum rated voltage of an alternative IGBT is $U_{ces\text{-max}}$, the bus voltage is expressed as

$$U_{dc} \leq M_4 \cdot U_{ces\text{-max}}$$

(18)

where $M_4 = 0.5$. By substituting (1, 4) into (18), the equation can be shown as

$$N_{p} \leq M_4 \cdot \frac{U_{ces\text{-max}} \cdot (M_1 \cdot U_p)}{P}$$

(19)

By substituting (19) into (16), the equation can be given as

$$N_{nt} \geq \frac{M \cdot U_p \cdot U_{\text{rated}}}{\sqrt{2M_1 \cdot P \left(\frac{T}{C_p} + R_p\right)}} - \frac{\sqrt{2} \cdot M_1 \cdot P \left(\frac{T}{C_p} + R_p\right)}{M_3 \cdot M_4 \cdot U_{ces\text{-max}} \cdot P \left(\frac{T}{C_p} + R_p\right)}$$

(20)

To better illustrate the constraint of IGBT on the selection of the ratio, the X-axis $N_{st}$ is replaced by the rated current of IGBT $\left[I = N_{st} \cdot (P/3)/(M_3 \cdot U_{\text{rated}})\right]$, and the Y-axis $N_p$ is replaced by rated voltage of IGBT $\left[U_{ces} = N_p \cdot M_1 \cdot U_p / M_4\right]$. The advantage of this process is that the voltage and current withstand values of IGBT can be observed intuitively when the $N_{st}$ changes.

As shown in Figure 3, for example, Infineon’s IGBT, the dotted frame represents the type of IGBT that can be selected. It can be found that, in some cases, there will be no suitable model of IGBT in the $N_{st}$ variation range. In this case, the rated current generally does not meet the requirements, so it is necessary to use the switch in parallel to reduce the current stress of each switch, but the parallel will also increase some design and control difficulties. Moreover, even with the proper type of IGBT, it can be replaced by parallel with some smaller rated current IGBT. Therefore, in the actual design, it needs a concrete analysis of specific situations.
3.2. The constraint of capacitor characteristics

In addition to switching devices, the influence of ultra-capacitor characteristics on the variation range of $N_{st}$ cannot be ignored. Table 1 shows the parameters of K2 series ultra-capacitor units produced by MAXWELL. In general, most ultra-capacitor manufacturers define the maximum impulse current of a unit by using the formula shown below.

$$I_p = 0.5 \times U_p \left( \frac{T}{C_p} + R_p \right)$$  \hspace{1cm} (21)

Table 1. parameters of K2 series ultra-capacitor units produced by MAXWELL.

| Type   | Unit 1 | Unit 2 | Unit 3 | Unit 4 |
|--------|--------|--------|--------|--------|
|        | BCAP06 | BCAP12 | BCAP20 | BCAP30 |
| Rated capacitance | 650F   | 1200F  | 2000F  | 3000F  |
| Rated voltage     | 2.7V   | 2.7V   | 2.7V   | 2.7V   |
| Equivalent series resistance | 0.8mΩ | 0.58 mΩ | 0.35 mΩ | 0.29 mΩ |
| maximum impulse current(1s) | 575A | 955A | 1585A | 2165A |

By solving the equation (16), it can be seen that when $N_{st}$ is calculated by the following expression, $N_p$ reach its minimum value.

$$N_{st} = \frac{M_1 \times U_p \times U_{rated}}{\sqrt{2 \times M_1 \times U_p \times (T/C_p + R_p)}}$$ \hspace{1cm} (22)

By substituting (22) into (12), the maximum discharge current can be given as

$$I_{dc\_max} = 0.5 \times M_1 \times U_p \left( \frac{T}{C_p} + R_p \right) = M_1 \times I_p$$ \hspace{1cm} (23)

In general, due to $M_1 < 1$, the maximum discharge current will not exceed the maximum pulse current of the capacitor. Therefore, by the constraint of equation(22), the range of $N_{st}$ is more precise.

By considering the constraints of IGBT and capacitor characteristics, the minimum value of $N_{st}$ is presented as

$$N_{st\_min} = \frac{M_1 \times M_2 \times U_p \times U_{rated}}{\sqrt{2 \times M_1^2 \times P \left( \frac{T}{C_p} + R_p \right)}} = \frac{\left( \sqrt{2 \times M_1^2 \times M_2 \times P \left( \frac{T}{C_p} + R_p \right)} \right)^2}{2 \times M_1 \times M_2 \times U_{dc\_max} \times U_{rated}}$$ \hspace{1cm} (24)

the maximum value of $N_{st}$ is expressed as
\[ N_{st, \text{max}} = \min \left( \frac{M_{U} U_{\text{rated}}}{\sqrt{2} M_{s} P \left( \frac{T}{C_{p}} + R_{s} \right)}, \frac{3M_{U} U_{\text{rated}} I_{e, \text{max}}}{P} \right) \] (25)

4. Experimental results

Table 2. Design index of a three-phase DVR.

| Parameter                              | Value  |
|----------------------------------------|--------|
| Rated power                            | 200kVA |
| Compensation time                      | 1s     |
| Phase voltage \(U_{\text{rated}}\)     | 400/\sqrt{3}V |
| Maximum injection voltage \(U_{d, \text{max}}\) | 400/\sqrt{3}V |

Table 2 shows the design index of a three-phase DVR. For the sake of achieving these targets, a 200kVA DVR device is established with a converter cabinet and a ultra-capacitor cabinet. Figure 4 depicts the prototype of DVR system. According to equation (24) and (25), the value of \(N_{st}\) is calculated as 1.2:1. The ultra-capacitor module, with 500A maximum discharge current, 11F total capacitance, and 720V rated voltage has been installed.

![Figure 4. Prototype of DVR system.](image)

The DVR device is tested under various voltage sag conditions. Figure 5 shows the waveforms of three-phase voltage sag compensation with a duration of 0.3s. Figure 6 shows the waveforms of single-phase voltage sag compensation with a duration of 1s. The upper waveforms are grid voltages, the middle waveforms are load voltages and the bottom waveforms are injection currents. It can be seen that the load voltages reach the rated values during the period of voltage sag. Experimental results obtained from the DVR system show the efficacy of the proposed design method.
Figure 5. Waveforms of three-phase voltage sag compensation (T=0.3s).

Figure 6. Waveforms of single-phase voltage sag compensation (T=1s).

5. Conclusion
According to the design index of DVR, the relationship between the ratio of series coupling transformer and the number of ultra-capacitor units is obtained, and the variation range of the ratio is limited by property and the characteristics of IGBT and ultra-capacitor. In this range, it is convenient to observe an suitable ratio to obtain high performance and low cost of energy storage device. The performance of the proposed design method has been verified by experimental results.

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References
[1] Bollen M H. Understanding power quality problems: voltage sags and interruptions. New York. IEEE Press, 2000.
[2] Guzman S A, Guzman O A etc. Analysis of voltage sag severity case study in an industrial circuit. IEEE Industry Applications Society Annual Meeting, 2015, 1-6.
[3] Wang Z J, Guo X Q etc. Impact of voltage sags on electric-vehicle charger and critical voltage sag determination. IEEE Transactions on Power Delivery, 2016, 31(3): 1397-1399.
[4] Weissbach R S, Karady G G, Farmer R G. Dynamic voltage compensation on distribution feeders using flywheel energy storage[J]. IEEE Transactions on Power Delivery, 1999, 14(2): 465-471.
[5] Buckles W E, Hassenzah W V. Superconducting magnetic energy storage. IEEE Power Engineering Review, 2000, 20(5): 16-22.
[6] Abdul Basith M B, Sunitha K. A novel approach of dynamic voltage restorer integration with ultra capacitor for proper voltage sag compensation. IEEE International Conference on Power, Control, Signals and Instrumentation Engineering (ICPCSI), 2017,578-582.
[7] Venugopal S, Agarwal V. A novel control strategy for an ultra-capacitor based dynamic voltage restorer with controllable dc-link voltage. IEEE 6th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), 2015,1-7.
[8] Preetha S, Bhavani R, etc. Design of ultra-capacitor based DVR for power quality improvement. International Conference on Circuit, Power and Computing Technologies (ICCPCT),2016, 1-8.
[9] Li B H, Choi S S, Vilathgamuwa D M. On the injection transformer used in the dynamic voltage restorer. In: Proceedings of IEEE ISIE, 2000, 941-946.