Research on the supercapacitor support schemes for LVRT of variable-frequency drive in the thermal power plant

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Abstract. In order to solve the problem of low voltage ride through (LVRT) of the major auxiliary equipment’s variable-frequency drive (VFD) in thermal power plant, the scheme of supercapacitor paralleled in the DC link of VFD is put forward, furthermore, two solutions of direct parallel support and voltage boost parallel support of supercapacitor are proposed. The capacitor values for the relevant motor loads are calculated according to the law of energy conservation, and they are verified by Matlab simulation. At last, a set of test prototype is set up, and the test results prove the feasibility of the proposed schemes.

1. Introduction

The low voltage ride through (LVRT) of the major auxiliary equipment’s variable-frequency drive (VFD) in the large thermal power plant is the key technical issue of power grid-source coordination. The grid voltage sag that occurs during power grid fault, power system oscillation and HVDC transmission block, will lead to the auxiliary VFD (e.g. coal feeder) trip and then cause the generator unit off-grid, which will further impact the power grid in the transient process, deteriorate the stability conditions. This issue has attracted the high attention from power grid corporation. In early 2014, State Grid Corporation of China issued a technical specification of high and low voltage ride through for the auxiliary VFD of the large-scale turbo-generator unit [1].

The LVRT capability of VFD is the ability to keep running when the AC supply voltage sags. According to IEEE1159 specification, the voltage sag is the abnormal events that voltage rms drops to 0.1 – 0.9pu and the duration is from 10ms to 1min. But, whether it is a voltage source or a current type VFD, the present conventional products cannot meet this specification, so it is necessary to study the LVRT support technique for such VFD.

Generally, VFD itself can maintain its control circuit working under 65-70% of the rated voltage. At this time, in order to maintain constant power output, it need more current, however, when the current exceeds a certain limit, VFD will trip due to overcurrent. For this reason, the existing solutions all focus on the external support. In general, they can be divided into two sorts: AC side support and DC link support.

AC side support schemes: 1) Dynamic voltage restorer (DVR)[2-3]. It is in series between power supply and VFD, its response time is fast, however the control is relatively complex. The actual support time depends on the energy storage unit, and the cost is higher, so there is few application for the VFD. 2) Online UPS. It is added at AC input side of VFD, in fact, considering the load characteristics of the drive, the larger capacity is needed which will increase the cost. Due to its
structure complexity and reliability, its application is also limited. 3) Dual AC power supply switching. Because the switching time is not fast enough, it cannot meet the technical requirements of LVRT, in fact, it can only do automatic restart or speed tracking starting for the VFD.

DC link support schemes: 1) The grid residual voltage boosting solution (AC-DC-DC), which once became the research hotspot [4-5]. Its principle is that the residual voltage of the grid under fault is rectified and then boosted to the voltage required by the DC link of VFD. Theoretically, it is a very good solution, and there has also been a certain application, but when AC residual voltage is low, the current requirement will be multiplied that need a larger power configuration, in addition, it cannot achieve zero voltage ride through. 2) Battery directly in parallel in the DC link, that is simple and there are more applications, but the battery life and maintenance issues become its biggest drawbacks. 3) To configure large capacitor in the DC link. At present, there are few reports about this kind of scheme, it is in the stage of research verification, so this paper will carry out such research.

This paper presents the scheme of supercapacitor paralleled in the DC link of VFD, its essence is using supercapacitor for energy storage to achieve LVRT support for VFD. With the characteristic of large capacity, small size, high efficiency of charge and discharge, long cycle life, the supercapacitor can be truly maintenance-free, this scheme has great advantages in nature. At present, supercapacitor has begun to put into industrial applications, in the fields of wind power generation and other new energy, the application research for LVRT and energy storage has also been carried out [6-9]. In this paper, two kinds of supercapacitor-support solutions (direct parallel and voltage boost parallel) for VFD are studied. Through the theoretical calculation, modeling and simulation, the key data of the capacitance under various powers are obtained, and the experimental prototype is built to test and verify the effectiveness of the schemes.

2. Scheme design

2.1. Basic principle

The main circuit of the conventional low-voltage VFD is AC-DC-AC structure, which includes rectifier unit, DC link and inverter unit. Most of them are the voltage source type, in which the middle DC link is parallel capacitor. In this paper, such VFD is the study object.

2.1.1. Solution A. The principle of solution A proposed is shown in figure 1. A certain capacity of supercapacitor group is connected to the DC link of VFD which is used to store energy. A blocking diode is connected to the DC port preventing the rectifier unit to bear extra charge current and to be overload. The supercapacitor charger should be configured separately. When the AC power supply is normal, the supercapacitor is in energy storing status, its terminal voltage is set lower than the normal output voltage of the rectifier unit. In case of grid voltage sags, the supercapacitor group will provide energy to the inverter to maintain the VFD running for a certain time.

2.1.2. Solution B. The principle of solution B proposed is shown in figure 2. A lower voltage supercapacitor group is applied and connected through a boost unit to the DC link of VFD. The boost unit is designed for constant output voltage control, and its voltage setting value is lower than the normal output voltage of the rectifier unit. When AC power is normal, there is no current output from the support device. In case of grid voltage sags, the supercapacitor group via its boost unit will provide energy for the inverter to maintain the VFD running for a certain time.

Compared with solution A, the advantages of solution B are as follows: 1) Because it can control the DC link voltage constant, so the output current of the VFD will not exceed the limit when AC voltage sags; 2) Deep discharge of supercapacitor can be achieved, the storage energy will be fully utilized; 3) Because the voltage of single commercial supercapacitor is low, this design can reduce the series number of capacitors, that also makes the voltage equalization control easy. The disadvantage is that a boost unit of the same power as the inverter unit is added, and taking account of the deep discharge, the input current rating shall be increased, that leads to an increase in cost.
2.2. Capacitance calculation method

The greater the load carried by the VFD, the greater the DC side current. When the AC voltage sags, in order to maintain a certain DC voltage and ensure that the VFD is not shutdown due to undervoltage or overcurrent, the larger supercapacitor is required. In following, the value of supercapacitor is calculated according to the low of energy conservation.

If $U_N$ is the initial discharge voltage, at the end of sag, the voltage becomes $U_i$. During this period, the energy $W_C$ released from supercapacitor $C$ can be expressed as:

$$W_C = \frac{1}{2} C \left( U_N^2 - U_i^2 \right)$$

At the same time, the energy consumption $W_M$ of VFD load can be expressed as:

$$W_M = P_M t$$

where $P_M$ is the motor load of VFD, $t$ is sag duration.

According to the low of energy conservation, regardless of the inverter loss, the energy released from the supercapacitor is equal to the energy consumed by the motor load:

$$W_M = W_C$$

Thus, the total capacitance value $C$ of the supercapacitor group can be obtained as follow:

$$C = \frac{2P_M t}{(U_N^2 - U_i^2)}$$

As the withstand voltage value of a single supercapacitor is low, the actual supercapacitor energy storage unit should be composed of many single supercapacitors in series and in parallel. The series number $N_S$ is determined according to the withstand voltage $U_S$ of single supercapacitor, and to leave proper voltage margin, then:

$$N_S > \frac{U_N}{U_S}$$

If the capacity of single supercapacitor is $C_S$ and the parallel quantity is $N_P$, then the total capacity $C$ of supercapacitor group can be calculated by (6):

$$C = \frac{N_P C_S}{N_S}$$
2.3. Voltage balancing and charging method
The present commercial supercapacitors, mostly are carbon material electric double-layer supercapacitors, their single capacitance value can reach to several thousands of Farad, but its withstand voltage is low. In the actual design for the supercapacitor series group, each capacitor max operation voltage should be lower than its withstand value, and should leave a certain margin. The terminal voltage fluctuation range of supercapacitor is large during charging and discharging process that is different from the battery, so the voltage equalization strategy is very important. There are a lot of voltage equalization technologies, e.g. voltage regulator tube method, switching resistance method, capacitor method, inductance method and DC/DC converter method, etc. [10-11]. The latter three are energy transfer type technology, which are the mainstream solutions.

In order to improve the performance stability of supercapacitor and reduce the influence of grid voltage fluctuation, the device should be designed using a dedicated charger, and the control function of constant voltage and current limit is requires.

3. Calculation and simulation

3.1. Supercapacitor parameter calculation
For a general application or under the light-overload use, the VFD selected with 110-120% overcurrent capacity is reasonable. So for the same rated output power, if its DC link voltage can be maintained within 0.8-0.9U_N, the VFD will be in stable operation.

When AC supply voltage is 380-400V, the DC link voltage of VFD is about 513-540V, the output voltage of the support device is designed lower than 513-540V in order to prevent its disordered discharge under normal AC status, the rated output DC voltage of the LVRT support device is set to 500-510V.

3.1.1. Solution A- Supercapacitor direct parallel scheme. In this case, the max sag duration of 5 seconds is required according to "Technical Specification for High and Low Voltage Ride Through of Major Auxiliary VFD of Large-scale Turbo-generator "[1] issued by State Grid Corporation of China. The rated charge voltage U_N of the supercapacitor group is designed to 510V by using 200pcs supercapacitors of single voltage 2.55V. The discharge end voltage drops to 90% and 80% U_N. The supercapacitor configuration values calculated by formula (4) are shown in table 1.

| Table 1. Capacitance values of Solution A. | Table 2. Capacitance values of Solution B. |
|-------------------------------------------|-------------------------------------------|
| VFD load | End voltage 90%U_N | End voltage 80%U_N | VFD load | End voltage 50%U_N | End voltage 90%U_N |
|----------|---------------------|---------------------|----------|---------------------|---------------------|
| 4kW      | 0.81F               | 0.43F               | 4kW      | 0.85F               | 3.37F               |
| 7.5kW    | 1.52F               | 0.80F               | 7.5kW    | 1.60F               | 6.32F               |
| 15kW     | 3.04F               | 1.60F               | 15kW     | 3.20F               | 12.6F               |
| 75kW     | 15.2F               | 8.01F               | 75kW     | 16.0F               | 63.2F               |

^a U_N=510V, sag time t=5s. ^a U_N=250V, sag time t=5s.

3.1.2. Solution B- Supercapacitor voltage boost parallel scheme. For this solution, the designed rated charge voltage U_N of supercapacitor group is 250V by using 100 pcs supercapacitors of single voltage 2.50V. The voltage 250V is close to the power plant's DC power supply system, in order to facilitate switchover if possible. Due to the constant output voltage control of the boost unit, so the deep discharge can be carried out, the supercapacitor group terminal voltage can drops lower, in theory, as long as the boost unit can maintain operating. Here we assume that the discharge end voltage drops to 50% and 90% U_N, the sag duration is 5 seconds as above, according to formula (4), the configuration values calculated are shown in table 2.
Compared with solution A, the same capacitance value of solution B can provide all the energy needed when it discharges to 50% $U_N$, the storage energy is full utilized. For the end voltage of 90% $U_N$, the latter's capacitance needed for the same power is about 4 times larger.

3.2. Simulation
Matlab/Simulink power system is used as simulation platform. According to the solutions proposed in this paper, the simulation circuits are constructed, the control mode of VFD is SPWM.

3.2.1. Solution A Simulation. According to the data in table 1, a 4kW VFD with 0.81F and 0.43F, and a 15kW VFD with 3.04F and 1.60F are simulated. The supercapacitor number in series is designed to be 200 and the max operating voltage of single supercapacitor is 2.55V, so the voltage of supercapacitor group is 510V when it is fully charged. Grid voltage sags to 0% for a duration of 5 seconds.

![Grid voltage sag waveform](image1)

(a) Grid voltage sag waveform.

![Super capacitor group voltage waveform](image2)

(b) Super capacitor group voltage waveform.

![Super capacitor discharge current waveform](image3)

(c) Super capacitor discharge current waveform.

**Figure 3.** Simulation waveforms of 4kW VFD LVRT (Solution A).

Figure 3 is simulation waveforms of the 4kW VFD LVRT, include grid voltage sag, supercapacitor group voltage and discharge current waveforms. Curve1 and curve 2 in figure 3(b) are terminal voltage waveforms of 0.81F and 0.43F respectively, when AC voltage returns to normal, the charger begins to charge the supercapacitor again. Figure 3(c) is supercapacitor discharge current waveforms, before and after the voltage sag, the discharge current is zero. During AC voltage sag, the VFD is maintained at...
the rated power status. The simulation end voltage values of discharge are shown in table 3, they are smaller than the calculation values, this is due to that the loss of inverter is not taken into account in calculation. The simulation results are basically consistent with the calculations.

| Load/capacitance | End voltage | Percentage |
|------------------|-------------|------------|
| 4kW/0.81F        | 450V        | 88.2%      |
| 4kW/0.43F        | 396V        | 77.6%      |
| 15kW/3.03F       | 451V        | 88.4%      |
| 15kW/1.60F       | 398V        | 78.0%      |

3.2.2. Solution B Simulation. According to the data in table 2, a 4kW VFD with 0.85F and 3.7F, and a 15kW VFD with 3.20F and 12.6F are simulated. The number of supercapacitors in series is designed to 100, and the max operating voltage of each capacitor is 2.50V, so the voltage of supercapacitor group is 250V when it is fully charged. Grid voltage sags to 0% for a duration of 5 seconds.

For the 4kW motor load, the simulation waveforms of grid voltage sag, supercapacitor terminal voltage and output voltage of boost unit are shown in figure 4. Figure 4(c) is output voltage waveform of boost unit, the voltage undershoot at the 2nd second and overshoot at the 7th second are caused by the inherent characteristics of the boost circuit, that is the negative regulation phenomenon in the event of a sudden load change, however which will not affect the basic performance of the LVRT support system. The boost output voltage is constantly controlled at 500V, and the VFD is maintained in operation at the rated power during AC voltage sags. The simulation end voltage values of discharge are shown in table 4, they are also smaller than the calculation values, this is due to that the loss of inverter and boost unit is not taken into account in calculation.

Table 4. The end voltage of supercapacitor group $(U_n=250V, t=5s)$.

| Load/capacitance | End voltage | Percentage |
|------------------|-------------|------------|
| 4kW/3.37F        | 223.6V     | 89.4%      |
| 4kW/0.85F        | 114.3V     | 45.7%      |
| 15kW/12.6F       | 223.8V     | 89.5%      |
| 15kW/3.20F       | 114.0V     | 45.6%      |

4. Test results
The supercapacitor of single capacity 400F/2.7V is used to build the test prototype, its technical parameters are shown in table 5. Figure 5 is the experiment scene in a factory, where the voltage sag generator is made of IGBT power components.

Table 5. The specification of single supercapacitor.

| Parameter          | Value           |
|--------------------|-----------------|
| Rated capacitance  | 400F (25℃)     |
| Capacitance deviation | -10%~+10%    |
| Rated voltage      | 2.7 V          |
| Rated discharge current | 70 A          |
| Max discharge current         | 135A          |

Figure 5. The experiment scene.

4.1. Solution A test
The test prototype uses 210 of 400F single supercapacitor in series, so the group capacitance is 1.90F. The rated voltage of group designed is 510V and single capacitor working voltage is 2.43V with some
voltage margin. The other parameters are shown in table 6. In the experiment, the motor load of VFD is 4kW, the measured waveforms of 5 seconds LVRT test are shown in figure 6.

Table 6. The specification of supercapacitor assembly (Solution A).

| Parameter                  | Value          |
|----------------------------|----------------|
| Rated capacitance          | 1.90F(25℃)    |
| Capacitance deviation      | -10%～+10%     |
| Rated voltage              | 510V           |
| Rated discharge current    | 70 A           |
| Max discharge current      | 135A           |
| Rated charging current     | 140 A          |

In figure 6, the AC voltage $U_{ac}$ drops to 60% pu for 5 seconds. The supercapacitor voltage $U_{dc}$ drops from 510V to 473V, because the experimental capacitance is larger than the simulation’s, so the final voltage is higher than the simulation result; $I_e$ is the supercapacitor discharge current; $n$ is the motor speed which is maintained at 1440rpm; $P$ is the motor power of constant 4kW. It is seen from figure 6 that the support device can fully meet the LVRT requirement of VFD.

4.2. Solution B test

The test prototype of Solution B uses 105 of 400F single supercapacitor in series, so the group capacitance is 3.81F. The rated voltage of group designed is 250V and single capacitor working voltage is 2.38V. The other parameters are shown in table 7. In the experiment, the motor load of VFD is 4kW also, the measured waveforms of 5 seconds LVRT test are shown in figure 7.

Table 7. The specification of supercapacitor assembly (Solution B).

| Parameter                  | Value          |
|----------------------------|----------------|
| Rated capacitance          | 3.81F(25℃)    |
| Capacitance deviation      | -10%～+10%     |
| Rated voltage              | 250V           |
| Rated discharge current    | 70 A           |
| Max discharge current      | 135A           |
| Rated charging current     | 140 A          |

In figure 7, the AC voltage $U_{ac}$ drops to 0% for 5 seconds; the supercapacitor voltage $U_{dc}$ drops from 250V to 207V; $I_e$ is the supercapacitor discharge current; $n$ is the motor speed. It can be seen from the figure, when the grid voltage drops, the support device outputs DC current for the inverter, DC link voltage is maintained at 500V, motor speed is constant 1440rpm and output power is constant 4kW. It is proved that the support device can fully meet the LVRT requirement of VFD also.

5. Conclusions

In order to improve the LVRT ability of VFD, this paper presents two technical schemes of supercapacitor paralleled in the DC link of VFD, they are supercapacitor direct parallel scheme(Solution A) and supercapacitor voltage boost parallel scheme(Solution B). The capacitance value is calculated according to the law of energy conservation, that is verified by Matlab simulation, the prototype test proves that the schemes are feasible, they can all achieve zero AC voltage ride through.
DC link directly paralleled with supercapacitor has the advantages of simple structure and easy implementation, can be used in high power occasions. DC link paralleled supercapacitor with a boost unit can maintain the DC link voltage constant, and ensure VFD not to be overcurrent, the LVRT performance is excellent. Compared with solution A, it saves half number of supercapacitors, and makes its voltage equalization relatively easy; deep discharge can be achieved, the storage energy of supercapacitor is fully utilized. But the boost unit capacity should be equal to the inverter unit, the cost increased and reliability issues cannot be ignored, this scheme has a certain advantage for the smaller VFD.

Compared with the battery scheme, the supercapacitor solution has advantages of a high efficiency, a long life cycle of charge and discharge, no pollution, maintenance-free. Besides for the auxiliary VFD in thermal power plant, the schemes can also be applied in the other industrial field.

References
[1] ZHENG Zhong, LI Weihua, GENG Hua and YANG Geng 2016 Review of LVRT technology for auxiliary equipment inverter of thermal power plant Electric Power Automation Equipment 36 pp 143-148
[2] Ghosh A and Ledvich G 2001 Structures and control of a dynamic voltage regulator (DVR) Proceedings of 2001 IEEE Power Engineering Society Winter Meeting (USA: Columbus, OH) 3 pp 1027-1032
[3] SHAO Wenquan, WANG Long, WANG Jianbo, WU Bo and YANG Yapeng 2015 Voltage sag immunity of coal feeder inverter in power plants Electric Power Construction 36 pp 88-93
[4] WANG Xiaoyu, ZHANG Tao, LIU Shu, CAO Fengmei, LIU Zhichao and YANG Qixun 2015 Power source with low-voltage ride-through capability for auxiliary equipment inverter of thermal power plant Electric Power Automation Equipment 35 pp 152-159
[5] LIU Yaozhong, MA Yonggang, WANG Guoqing and DU Jianbin 2014 A design of low voltage ride through power supply based on thermal power plant auxiliary transducer Power Electronics 48 pp 13-15
[6] WANG Peng, WANG Han, ZHANG Jianwen, CAI Xu and HAN Zhengzhi 2014 Design and application of supercapacitor energy storage system used in low voltage ride through of wind power generation system Proceedings of the CSEE 34 pp 1528-1537
[7] Abbey C and Joos G 2007 Supercapacitor energy storage for wind energy applications IEEE Transactions on Industry Applications 43 pp 769-776
[8] ZHANG Guoju, TANG Xisheng and QI Zhiping 2010 Application of hybrid energy storage system of super-capacitors and batteries in a microgrid Automation of Electric Power Systems 34 pp 85-89
[9] Tian H, Gao F and Ma C 2012 Novel low voltage ride through strategy of single-stage grid-tied photovoltaic inverter with supercapacitor coupled IEEE 7th International Power Electronics and Motion Control Conference - ECCE (Asia Harbin, China) 2 pp 1188-1192
[10] Qi Xinchen, Li Haidong and Qi Zhiping 2008 Overview of supercapacitor equalization technology High Voltage Engineering 34 pp 293—297
[11] ZHANG Li, WU Yanping, LI Chen, Wang Kai and Zhang Ning 2014 Control strategy for balanced discharge based on supercapacitor storage system Transactions of China Electrotechnical Society 29 pp 329-333