A Novel High-Speed Flywheel Based DC Voltage Source with Soft Handover Capability

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Abstract—A novel high-speed flywheel-based DC voltage source (FDSC) has recently been developed as a direct and improved energy storage substitute for chemical batteries in uninterruptible power supply (UPS) applications. Like chemical batteries, the FDSC requires only a DC connection to a UPS with no other interconnections; however, the FDSC offers many advantages over chemical batteries, including reduced life cycle costs due to elimination of the periodic replacement of chemical batteries, increased power density, known state of charge, and the absence of environmentally harmful materials. The FDSC also incorporates a novel soft handover feature which was developed to provide a gradual load transfer from the backup energy source of the UPS to a backup engine-generator set (genset). In the absence of the soft handover feature, the genset fails due to its inability to slew its output power in the time required to continue to supply the critical load. This paper details the performance of the FDSC during operational events and shows the benefits of the soft handover feature for a combined genset-UPS ride-thru application.

I. INTRODUCTION

A novel dc voltage source incorporating high-speed flywheel based energy storage has been developed as a direct and improved substitute for chemical batteries in applications which require moderate periods of energy transfer but at high power levels. An example of such an application is the provision of energy storage for a double conversion uninterruptible power supply (UPS) during the period of time that the mains power is lost and until a backup engine-generator set (genset) can be started and brought on line. Due to the use of a high-speed flywheel for energy storage, the flywheel-based dc source (FDSC) has several advantages over chemical battery based systems including: reduced life cycle costs due to elimination of the periodic replacement of chemical batteries, increased power density, known state of charge, and the absence of environmentally harmful materials. Furthermore, the lifespan and rated performance of the FDSC are not affected by the number or depth of discharge cycles.

This paper details the operation and performance of the FDSC in a typical UPS ride-thru application as discussed above and demonstrates the benefits of the FDSC's soft handover feature. This feature allows the load power to transfer gradually from the FDSC to the genset thereby

greatly reducing the magnitude of the genset output voltage and frequency sags which occur during the transient conditions of the load handover period due to the genset's limited power slew rate capability. Such voltage and frequency sags can exceed 20% and 5% respectively and can cause the input rectifier of the UPS to trip off due to an under voltage or under frequency condition resulting in the failure of power to the critical load. The soft handover feature eliminates the traditional need to greatly oversize the genset to obtain improved transient performance during the load handover from a short term energy supply to the genset [1].

II. FDSC DESCRIPTION

The FDSC consists of high-speed flywheel with an integral permanent magnet synchronous motor-generator connected to a 3-phase inverter. The steel flywheel spins in a partial vacuum, is levitated on active magnetic bearings, and stores 4.51 MJ (1.25 kWh) at 36,000 r/min. The motor-generator and inverter are designed to provide a maximum power of 125 kW, which is available as a dc voltage and current at the terminals of the FDSC in the same manner as with chemical batteries. At maximum power the FDSC is designed to support a load for 20 seconds. Longer durations can be obtained at lower power levels.

III. TYPICAL FDSC OPERATION

The FDSC is shown schematically in Fig. 1 along with the additional components of a typical genset-UPS ride-thru application. During normal operation the automatic transfer switch (ATS) is connected to the mains; power flows from the mains to the critical load via the rectifier and inverter of the UPS. Additionally, a small amount of power flows from the mains via the rectifier to the FDSC to initially charge the flywheel and then subsequently to maintain the charge. Upon a mains failure, the critical load is powered by the FDSC from energy stored in the flywheel until the genset's engine can be started, its output voltage has stabilized, and the ATS can be switched to the genset. This time period that the FDSC must power the load is termed the ride-thru time. After the ATS has been switched to the genset, the genset provides power to the load and to the FDSC, in a similar manner as the mains.

Fig. 1. FDCS connected into typical UPS ride-through application

At the end of the ride-thru period, the critical load power is gradually (i.e. softly) handed over from the FDCS to genset over a period of a few seconds. That is, the portion of the load power provided by the genset is slowly ramped up while the portion provided by the FDCS is slowly ramped down. As mentioned above, to avoid an excessive voltage sag at the input of the rectifier, the load power must not be applied to the genset in a single step. The soft handover time can be tailored to suit the application and the benefits of it can be understood by considering the following discussion.

IV. BACKUP ENGINE-GENERATOR SET PERFORMANCE

In a typical backup engine-generator set an internal combustion engine is configured as a prime mover driving an ac alternator, commonly referred to as a generator. Compared to the mains in most UPS applications, the engine provides a considerably reduced power capability and the generator's impedance is many times larger. These two disadvantages mean the transient performance of the generator will suffer compared to the mains. This fact can be seen by examining Fig. 2 which compares the step response to a 125 kW resistive load of a 480 V, 60 Hz mains to a 480 V, 60 Hz backup genset. The genset is composed of a 4-pole permanent magnet synchronous generator rated for 317 kW driven by a diesel engine with a prime power rating of 350 kW. While the mains are very stiff in response to the step load, the generator voltage, output power and frequency sag more than 15%, 20%, and 5% respectively. Note these sags occur even with the genset being rated for a steady state load of more than twice that applied. To improve the transient performance of the genset, the traditional solution would be to oversize it further.

The voltage and frequency sags presented above are great enough to not only trip off sensitive loads but more robust loads as well such the UPS from Fig. 1. For example, Fig. 3 shows the results of a 125 kW step load applied to the output of the UPS inverter in Fig. 1 while the input rectifier is powered from the backup generator. The FDCS was not connected to the UPS during this test. The UPS used for the

Fig. 2. Normalized step response of mains and genset to a 125 kW load

Fig. 3. Normalized step response of genset to a 125 kW load fed via UPS

test can tolerate rectifier input voltage and frequency sags of 20% and 5% respectively. However, even these wide margins are violated by the sluggish response of the generator which caused the UPS to trip off (occurring at approximately 2.8 seconds in Fig. 3). Similarly, it is apparent the power output of the generator never climbed high enough to meet the load demand (1 p.u.).

V. FDCS PERFORMANCE

A. Soft Handover Enabled

To reduce the genset voltage and frequency sags, the FDCS was developed with a soft handover feature, thereby

allowing the load demand on the genset to increase gradually. Fig. 4 shows the operation of the FDCS while connected into the complete genset-UPS ride-thru application of Fig. 1. At time zero in Fig. 4 the 480 V, 60 Hz mains are on and a 125 kW load (1 per unit) is being supplied. The input power is initially greater than 1 p.u. since losses in the UPS must be supplied. At about 2 seconds into the test the mains are switched off and it is clear that the input voltage and power decrease to zero. The flywheel, which was initially charged to 36,000 r/min, begins to slow as the FDCS transfers the stored rotational energy onto the electrical output bus of the FDCS. It can be seen that the output power of the FDCS rises rapidly to supply the 1 p.u. load and the losses of the UPS inverter.

At approximately 15.5 seconds, the genset has been started and the ATS connects the generator to the UPS input rectifier. After a 1 second initialization time, the rectifier becomes active and begins to pull power from the genset. At this point the FDCS softly transitions the critical load to the genset over 3.5 seconds as shown by the ramps in the input power and FDCS power plots. At the end of the test the flywheel has slowed to 25,700 r/min. To recharge the flywheel and to supply the load the input power rises above 1 p.u. During this time it can be seen that the FDCS power is negative. Throughout the entire test the load power remains constant and the generator voltage and frequency are well controlled throughout the load transition process.

B. Soft Handover Disabled

To further illustrate the benefit of the soft handover feature, Fig. 5 shows the results from a similar test to the one described above except that the soft handover feature is disabled. During the test a 125 kW load is connected to the output of the UPS inverter. At a time of 1.8 seconds the mains are switched off and the FDCS supports the load as expected. At 13 seconds the ATS connects the UPS rectifier to the genset. This time however, instead of softly transitioning the load power to the genset, the full load is applied to the genset over a 0.3 second interval.

Fig. 5 shows that the genset clearly cannot tolerate such a quick load transition. When the load is applied to the genset, the generator voltage sags 13% and the frequency sags more than 5%. Dips of these magnitudes cause the FDCS to intervene and support the load. While the load is carried by the FDCS the genset recovers and its output voltage stabilizes. This signals the UPS rectifier to begin pulling power; the FDCS quickly relinquishes the load to the genset and the cycle of the generator failing to pick up the load continues. Using the soft handover feature ends this cycle of load transition failures as was shown in Fig. 4. For completeness, Fig. 6 shows the load transition failures of Fig. 5 in greater detail.

Fig. 4. FDCS operation during mains failure with soft handover feature

Fig. 5. FDCS operation during mains failure without soft handover feature

Fig. 6. Detail of load transition failure cycles

VI. BACKUP ENGINE-GENERATOR SET SIZING

The objective of this section is to present the correlation between the generator voltage and frequency sags as a function of load power with the soft handover feature enabled and disabled. Furthermore, it is desired to determine the power level at which the genset can receive the load without the soft handover and without load transition failure cycles emerging. This data will allow a figure of merit to be established that expresses the amount the alternator needs to be oversized in order to successfully receive the load without the soft handover feature.

Figs. 7 and 8 show the maximum voltage and frequency sags respectively at the output of the generator during the load transition from the FDSCS to the genset. The data is presented for when the soft handover feature is both enabled and disabled as a function of the load power level. In Fig.7 it can be seen that the maximum voltage sag is less than 1% when the soft handover is used. Without the soft handover, the genset is only capable a receiving up to a 100 kW load. Above this power level, load transition failure cycles emerge as the generator is unable to receive the load as was discussed in the section above.

Fig. 8 shows similar behavior to Fig. 7. The maximum frequency sag for the soft handover case is less than 1.8%. The genset fails to receive the load transition above the 100 kW level with the soft handover disabled.

The data from Figs. 7 and 8 allow an alternator oversize rating to be determined for when the soft handover feature is not used. As was mentioned previously, the genset used for the testing in this paper has an alternator power rating of 317 kW and the prime power rating of the diesel engine is 350 kW. Referring to Fig. 1, it can be seen that when the genset is supporting the load it must also supply the UPS losses. It has been found experimentally that the UPS efficiency is about 90%. Thus for the 100 kW load which was the largest load the genset could successfully receive without the soft handover, the genset must source a total of approximately 111 kW. For this exercise the flywheel charging power can be neglected as it is small.

The amount the alternator is oversized can be computed as the rating of the alternator divided by the power demand which is

$$\frac{\text{Alternator Rating}}{\text{Power Demand}} = \frac{317 \text{ kW}}{111 \text{ kW}} = 2.85. \quad (1)$$

An oversize rating of 2.85 is economically and logistically undesirable. Furthermore, such an oversize rating – needed to ensure good dynamic performance – brings up concerns of too lightly loading the genset during steady state operation.

VII. FUTURE WORK

The above disadvantages can be avoided by using the FDSCS with the soft handover feature. With the soft handover, the oversize rating can be greatly reduced. For

Fig. 7. Maximum generator voltage sag during load transition from FDSCS

Fig. 8. Maximum generator frequency sag during load transition from FDSCS

example, while the largest load the FDSCS can support is 125 kW due to power electronics limits, by employing (1) and the UPS efficiency, a maximum oversize rating of 2.28 can be calculated. To determine the minimum oversize rating that is possible when using the soft handover feature, testing with lower rated gensets is needed. The authors intend to perform this testing in future work.

VIII. CONCLUSION

The flywheel based dc source discussed above offers a number of advantages compared to chemical batteries for applications which require moderate energy storage but high power capability, including longer life, known state of charge, and an insensitivity to the number or depth of

discharge cycles. The soft handover capability of the FDCS provides a means by which the load power can be gradually transitioned from the FDCS as the backup energy source to the genset as the backup energy source. This gradual transition reduces the transient performance required by the genset. Since increased transient performance is typically obtained by over sizing the steady state capability of the backup genset, the reduced requirement means smaller

generator sets can be specified than would otherwise be possible.

REFERENCES

- [1] D. C. Vanderbrook, "Fundamentals of the Power Quality / Power Reliability System Application Process," *Proceedings of the 2004 Power Quality Conference*, November 2004.