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Coordination of UFLS and UFGC by Application of D-SMES

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***Abstract*-- In this paper, the authors studied the coordination of under frequency load shedding (UFLS) and under frequency governor control (UFGC) by applying the distributed superconducting magnetic energy storage (D-SMES) devices. The active power of D-SMES device is controlled to eliminate the initial rapid frequency drop and allow time for the full action of UFGC to take over. The reactive power of D-SMES is controlled to stabilize the local bus voltage. The research results show that D-SMES devices can damp the quick dropping of system frequency and hold it waiting for the full activation of system spinning reserve. D-SMES can help the governors output their maximum reserve before UFLS drops more load.**

***Index Terms*—system stability, spinning reserve, under frequency governor control, under frequency load shedding, distributed superconducting magnetic energy storage (D-SMES).**

I. INTRODUCTION

One of the most undesirable conditions for power system operation is the loss of generator units or transmission lines causing big power-load unbalance. This kind of unbalance will cause the drop of power system frequency from its steady state. If not properly counteracted it can lead to major stability problems [1]. The typical protection scheme for such conditions is under frequency load shedding (UFLS) to stop the frequency drop after generation-load unbalance happens. UFLS is a final action to mitigate the severe consequences [2].

Load shedding is accomplished by frequency sensitive relays. The relays measure the frequency and rate-of-change of frequency to disconnect load. UFLS is usually implemented in several stages with each stage to shed a particular amount of load at its frequency setting point [3].

In most severe generation-load unbalance conditions, the frequency drops so quickly that the governor cannot fully activate spinning reserve. Most of the time, UFLS serves as a tool to prevent the system collapse before governor can fully activate spinning reserve quickly enough to restore the system to its normal operating frequency. This may results in over-shedding.

The underfreqeuncy governor control (UFGC) cannot help to prevent system from collapse by activating system reserve quickly because of its inertia. UFLS happens before UFGC has the time to take full action. Unfortunately, no method exists to coordinate these two functions right now [4].

As an example of energy storage system (ESS) technology, D-SMES system has the advantages in both energy storage ability and flexibility of its power electronics interface [5]. D-SMES has been employed due to its capability to work as active and reactive power generation and absorption systems. Besides the task of voltage control, it may also be applied to improve the transmission capability and system stability [6,7]. The application of D-SMES can provide a direct way to coordinate the UFLS and UFGC. It can help to fully activate the system spinning reserve, which can prevent over shedding.

In this paper, the authors analyzed the coordination of UFLS and UFGC by D-SMES application. The reason for using D-SMES rather than a concentrated SMES is to coordinate the UFGC locally. The application of D-SMES is to support the active energy to stop the quick drop of system frequency and wait for the full performance of UFGC which can fully activate the system spinning reserve, result in avoiding over shedding.

II. ANALYSIS OF SYSTEM FREQUENCY CHARACTERISTICS

A 23 bus sample system is used in the study. Fig. 1 is the one-line diagram of the system. In this system, the total generation is 3258MW+j964MVAR and the total load is 3200MW+j1950MVAR. Four 250MVA, 100MW D-SMES [8] will be installed at the generator buses 101, 102, 206 and 211. The reason for using D-SMES rather than a concentrated SMES is to coordinate the UFGC locally.

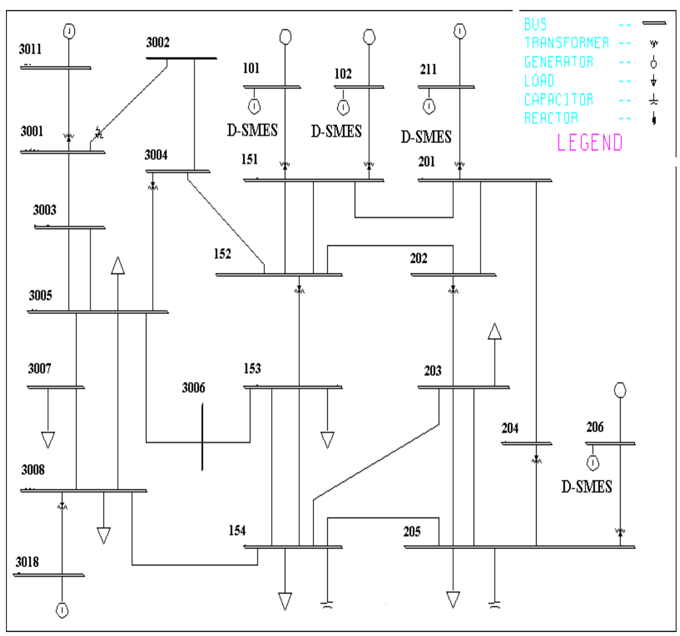


Fig. 1. One-line diagram of the sample research system.

Information about generators and loads in the system is listed in Table 1 and Table 2 respectively. In Table 1, Gen.206 (generator connected to bus 206) has a high reactive power output (600MVAR) which may cause obvious change of the system voltage when it is tripped out of the system.

TABLE 1 GENERATORS INFORMATION OF THE SYSTEM.

Gen Bus No.	P_G (MW)	P_G%	Q_G (MVAR)	Q_G%
101	753	23.1	81	8.4
102	753	23.1	87	9
206	800	24.6	600	62.2
211	600	18.4	17	1.8
3011	258	7.9	104	10.8
3018	100	3.1	80	8.3

TABLE 2 LOAD INFORMATION OF THE SYSTEM.

Load Bus No.	P_L (MW)	P_L%	Q_L (MVAR)	Q_L%
153	200	6.3	100	5.1
154	1000	31.3	800	41
203	300	9.4	150	7.7
205	1200	37.5	700	35.9
3005	100	3.1	50	2.6
3007	200	6.3	75	3.8
3008	200	6.3	75	3.8

According to the PSS/E software requirement, the constant MVA load is not realistic for voltages below 0.8 per unit. The constant load in Table 2 has been converted into 50% constant current load and 50% constant admittance load according to the following rules [9].

$$S_I = \frac{aS_P}{v} \tag{1}$$

$$S_Y = \frac{bS_P}{v^2} \tag{2}$$

Where S_P is the original constant load, a and b are load transfer fractions, and v is the bus voltage magnitude when load conversion is made.

For the dynamic characteristics of the above load mix, the change of voltage and frequency may cause changing the value of the active and reactive of load.

Fig. 2 is the frequency at 5 different buses when generator at bus 101 (referred as Gen.101) is dropped. The buses are generator buses (bus 101 and bus 211), load buses (bus 154 and bus 3005) and tie line buses (204). We can see that the frequencies of all the buses in this system have the same dynamic characteristics, which is clearly seen from Fig. 3. So we select the frequency of bus 154 as the representative of the study.

Fig. 3 is the frequency dynamics for all buses in the system when Gen.101 is tripped, from which we can draw the conclusion that the frequency of all the buses in the system has the same dynamics.

Fig. 4 and Fig. 5 are the frequency and voltage dynamics of bus 154 when different generator is tripped from the system. In Fig. 4, the frequency drop caused by Gen.206 tripping is much lower than that caused by Gen.211 tripping even though the active power of Gen.206 (800MW) is much larger than that of Gen.211 (600MW). The reason lies in the fact that larger reactive power (600MVAR) has been dropped from the system when Gen.206 is tripped. That causes the voltage of the whole system dropping to a very low level (from 0.94 pu to 0.8 pu), which is shown in Fig. 5. The whole load of the system will become smaller because of the dynamic load characteristics mentioned above. The sudden drop of Gen.206 causes large voltage drop that the frequency rises above 60 Hz at the beginning of the dynamics.

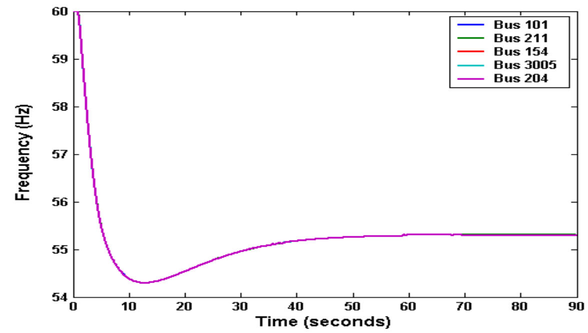


Fig.2 Frequency of different buses when generator at bus 101 is disconnected.

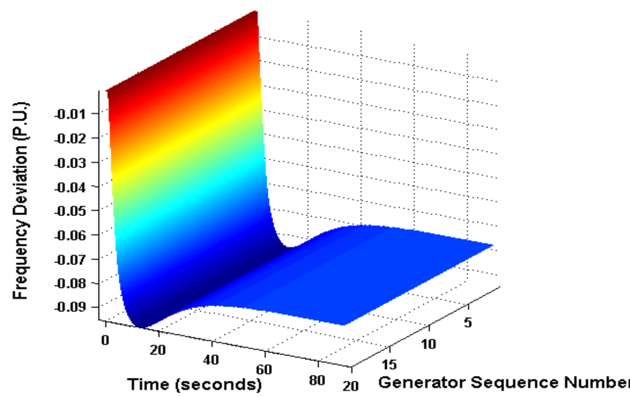


Fig. 3. The frequency dynamics of all the buses in the system when Gen.101 is tripped.

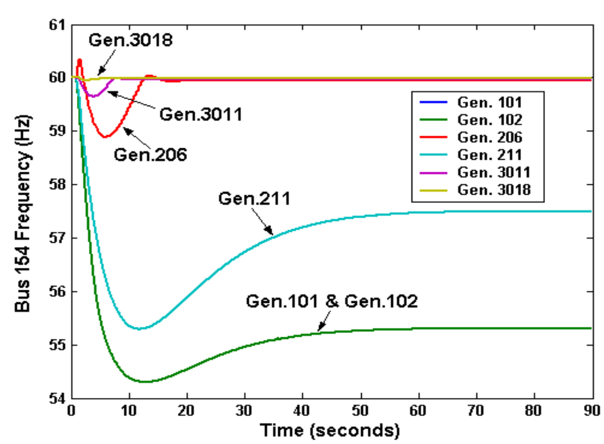


Fig. 4. Frequency of bus 154 when different generator is disconnected from the system.

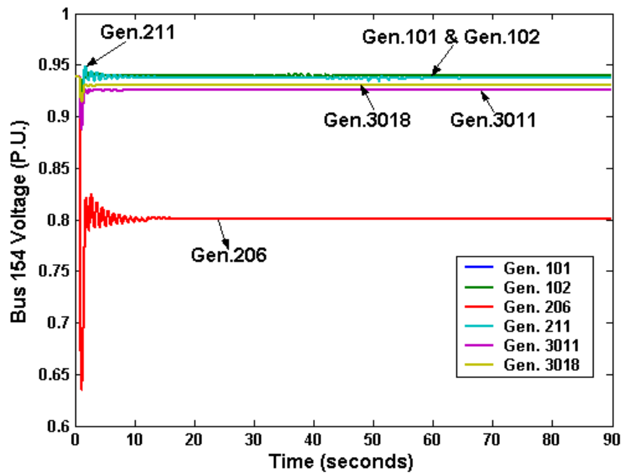


Fig. 5. Voltage of bus 154 when different generator is tripped from the system.

During the frequency dynamics in Fig. 4, the frequency will recover to some level because the output of the UFGC will increase from the frequency drop. Fig. 6 is the dynamic governor output of Gen.101, Gen.102 and Gen.206 when Gen.211 is tripped. We can see that the governor output will rise to its highest point after a long time (about 20 seconds) because of the inertia. But the frequency will drop to its lowest point within a short period of time (within 10 seconds) in Fig.4. If there is UFLS in the system, the UFLS will act before the governors output their full reserve. UFLS will drop more loads. That may cause the unsufficient usage of system spinning reserve. The total active power reserve of Gen.101, Gen.102 and Gen.206 is about 400MW.

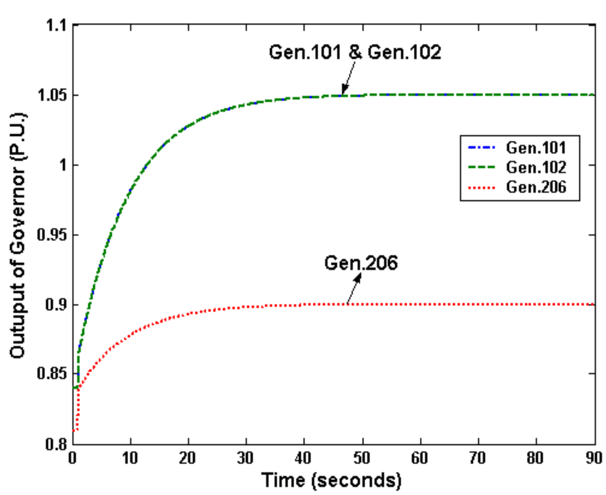


Fig. 6. The governor output of Gen.101, Gen.102 and Gen.206 when Gen.211 is tripped.

III. Effects of D-SMES On System Frequency Dynamics

The configuration of D-SMES in this study consists of three main parts shown in Fig. 7: an energy storage system as superconducting magnetic energy storage system, a power converter, and a transformer. The converter produces a three-phase voltage at the secondary winding of the transformer. This voltage can be varied in magnitude and phase with respect to the voltage on the high side of the transformer. The reactive power exchange between the converter and the ac system is controlled by varying the phase of the secondary voltage, the converter, effectively, a STATCOM that has the added feature of facilitating active power flow between its dc and the ac side.

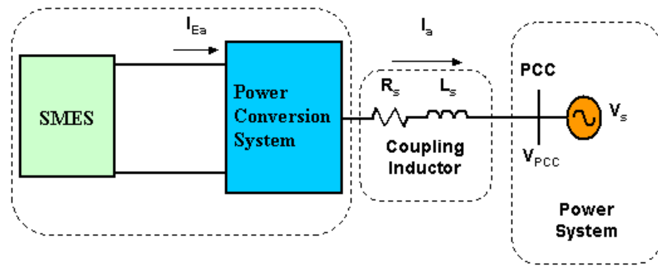
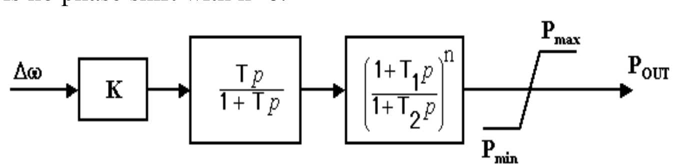
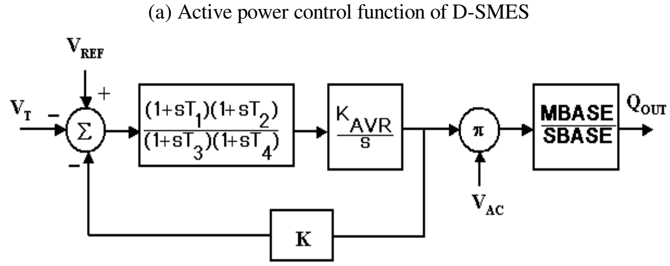


Fig. 7. The configuration of D-SMES.

The control functions of the D-SMES have two parallel independent parts for active power control and reactive power control. The active power control is to control the active power output of D-SMES to stop the quick drop of system frequency [10]. The reactive power control is to keep the terminal voltage at the reference value [9]. Fig. 8 is the control blocks of the two parts. In Fig. 8 (a), the K in the first block is the multiplying factor. The second block is the resetting block which makes P_{out} zero when $t \to \infty$. The third block is a phase compensation block which will make P_{out} be synchronous with $\Delta\omega$. In Fig. 8 (b), K_{AVR}, T_1, T_2, T_3, and T_4 are the gain and time constants of the automatic voltage regulator. K is the negative feed back factor. In our case, there is no phase shift with n=0.



(a) Active power control function of D-SMES



(b) Reactive power control function of D-SMES

Fig. 8. Control function chart of D-SMES controller.

In this study, the 4 D-SMES are installed at the generator buses (as 101, 102, 206 and 211) as shown in the one-line-diagram in Fig. 1 according to the generator information in Table 1. In this paper, we use the case of tripping Gen 211 as the sample of the study, because the generation of Gen 211 is big enough and there is no spinning reserve in Gen 211.

Fig. 9 is the dynamics of frequency at bus 154, Gen.101 governor output, active power output of D-SMES when Gen.211 is tripped from the system. In Fig. 9 the active power control of D-SMES slows down the drop of frequency and keeps it in a high level for a period of time during which the output of generator governor rises to its highest point. The frequency will continue to drop after D-SMES outputs all its active energy. But the lowest frequency is much higher than that if there is no D-SMES in the system because of the fully activation of system spinning reserve.

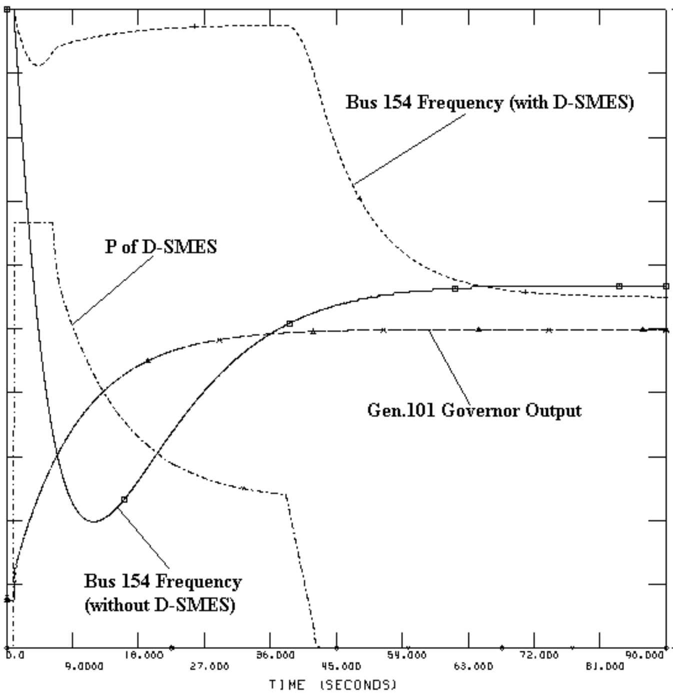


Fig. 9. Effects of D-SMES on the system dynamics when Gen.211 is tripped

Fig. 10 is the comparison of frequency of bus 154 when Gen. 211 is tripped. The active power of D-SMES is controlled to keep a small frequency drop, 0.4Hz for example, to keep the governor output rising.

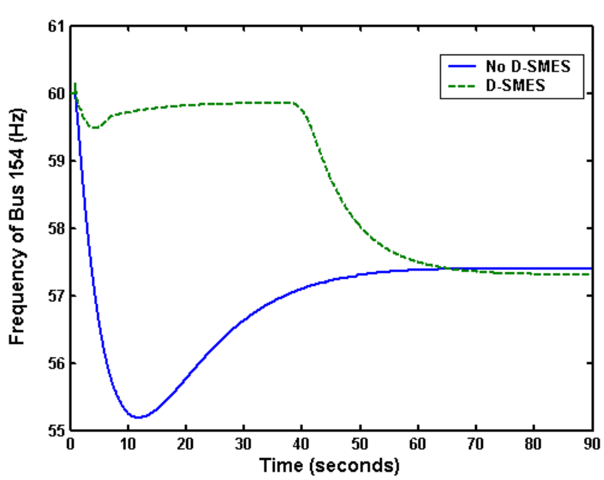


Fig. 10. Comparison of frequency of bus 154 when Gen.211 is tripped.

Fig. 11 is the active power and reactive power output of D-SMES on 101 bus. The curve part (from 6.3s to 38.2 s) of active power output is controlled to keep 0.4 Hz frequency drop shown in Fig. 10 to keep the governor output rising. D-SMES outputs reactive power to keep the bus voltage at the reference value.

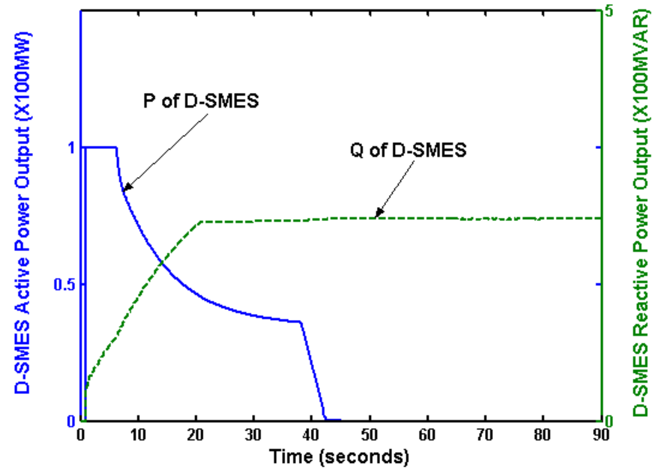


Fig. 11. D-SMES active and reactive power output when Gen.211 is tripped.

IV. Coordination of UFLS and UFGC by D-SMES

As we mentioned above, there is no method to coordinate UFGC and UFLS [4] by now. Quite often this leads to an amount of disconnected load that is far more than necessary and may even lead to large frequency oscillations [3].

In this study, we use D-SMES to coordinate the UFGC and UFLS. The application of D-SMES can make the UFLS more effective to reduce the influence on power consumers by minimizing the amount of load to be shed [3].

In this research we chose a three step UFLS scheme to study the application of D-SMES in UFLS. The UFLS scheme is shown in Table 3.

TABLE 3 UFLS SCHEME TABLE

Step	f_i (Hz)	t_i (s)	P_{LSi} (%)
1	59.5	0.2	9
2	59.0	0.2	8
3	58.5	0.2	8

Fig. 12 is the UFLS protection result when Gen.211 is tripped if there is no D-SMES in the system. From the figure of load on bus 153, we can see that all the three load-shedding steps shed 25% of the total load. Even though the governor output begins to rise after the drop of Gen.211 but it stops and drops to almost the original level because the quick action of ULFS improves the system frequency to almost 60 Hz. In this situation, almost no system spinning reserve has been activated to restore the system frequency to its normal value. At the beginning of dynamics the drop of load on bus 153 is caused by the voltage dip because of the load dynamic characteristics mentioned above.

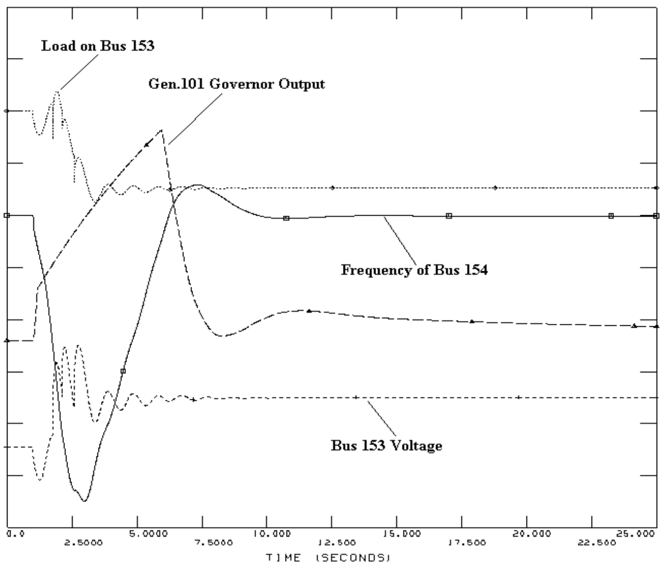


Fig. 12. Results of UFLS protection when Gen.211 is tripped. (There is no D-SMES in the system.)

Table 4 shows the protection effects of the UFLS if there is no D-SMES in the system. We can see that very large amount of load which is far more than necessary has been shed. But the governor does not output its full active reserve. For example, there is about 380 MW active power reserve left for Gen.101, Gen.102 and Gen.206 when Gen.211 is tripped. That is shown clearly in Fig. 12.

TABLE 4 EFFECTS OF UFLS ACTION. (THERE IS NO D-SMES)

Tripped Gen.	Action Steps	f_{min} (Hz)	f_{final} (Hz)	Shed Load (%)
101	3	58.0	59.5	25
102	3	58.0	59.9	25
206	2	59.0	60.0	17
211	3	58.3	60.0	25
3011	0	59.6	59.96	0
3018	0	59.9	59.99	0

Table 5 shows the effects of the UFLS when there are 4 D-SMES in the system. We can see that with the help of D-SMES, the generator governor can output its most spinning reserve. Less load has been shed. For example, there is about 130 MW active power reserve left for Gen.101, Gen.102 and Gen.206 when Gen.211 is tripped and the UFLS acts. About 324MW spinning reserve has been activated, which is larger than that (about 260MW) controlled by a 1000MVA, 400MW concentrated SMES. That is shown clearly in Fig. 13.

TABLE 5 EFFECTS OF UFLS ACTION. (THERE IS D-SMES)

Tripped Gen.	Action Steps	f_{min} (Hz)	f_{final} (Hz)	Shed Load (%)
211	1	59.46	59.93	9

In Fig. 13, the load on bus 153 has been dropped 9% by the first UFLS step. The combination of D-SMES and governor prevent the system frequency dropping to the second shedding setting point of 59.0 Hz which is shown in Fig. 14. The activating of system spinning reserve restore the frequency to its normal value during which D-SMES runs almost out of its storage energy which is shown in Fig. 15 and Fig. 16.

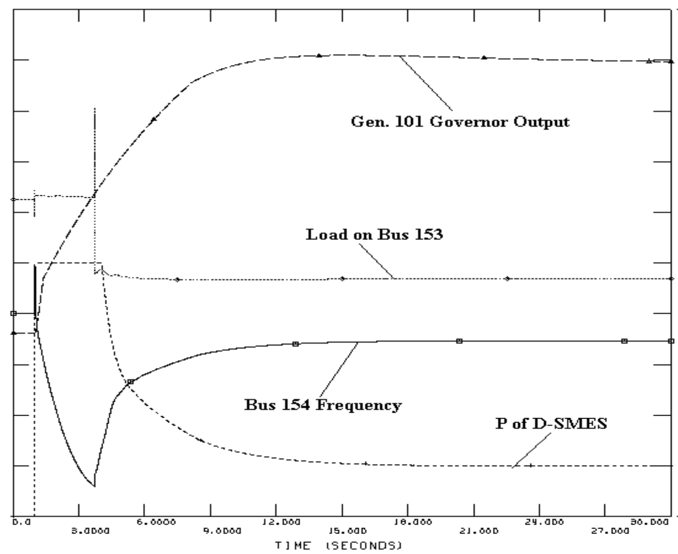


Fig. 13. Results of UFLS protection when Gen.211 is tripped. (There are D-SMESs on the generator buses.)

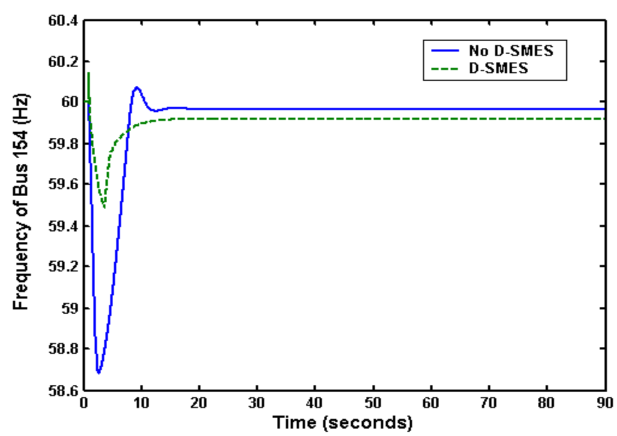


Fig. 14. Comparison of Bus 154 frequency for different situations under UFLS when Gen.211 is tripped.

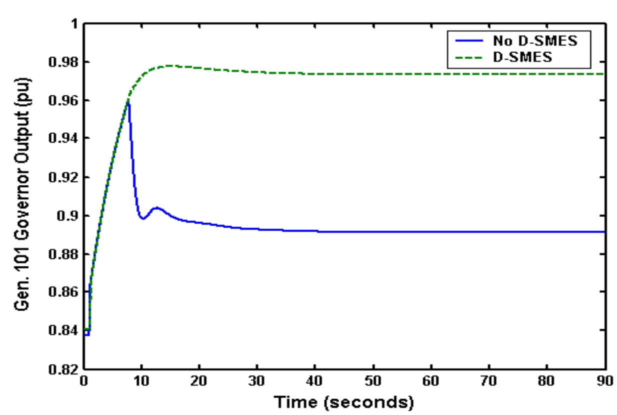


Fig. 15. Comparison of Gen. 101 governor output for different situations under UFLS when Gen.211 is tripped.

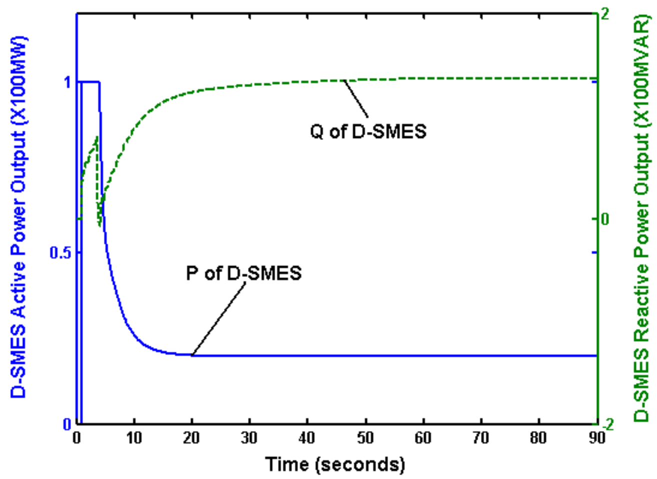


Fig. 16. D-SMES active and reactive power output under UFLS when Gen.211 is tripped.

In Fig. 17, we can see that UFLS drops 25% load in three shedding steps on bus 153 if there is no D-SMES in the system. When there are 4 D-SMES in the system, the ULFS only drops 9% load in one shedding step on bus 153. The reason for the load fluctuation on bus 153 is the voltage fluctuation of bus 153 as shown in Fig. 12. The voltage fluctuation changes the value of the load as explained in section 2.

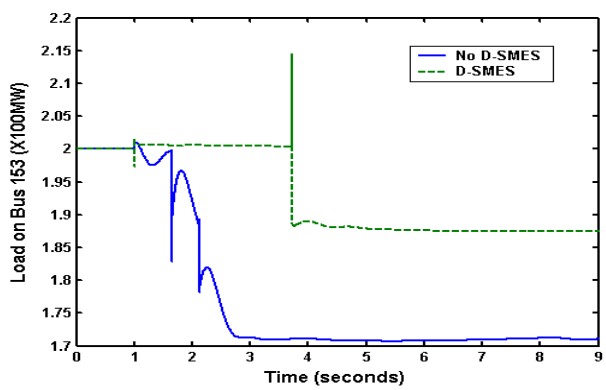


Fig. 17. Comparison of load on bus 153 for different situations under UFLS when Gen.211 is tripped.

V. Conclusion

UFGC and UFLS are two general control schemes to restore power system frequency to the normal value when generation-load unbalance causes drop of system frequency. UFGC is used to activate the system spinning reserve and UFLS is used to shed an amount of load to stop the dropping of the system frequency. Even though UFLS serves as the last-resort to prevent the system from collapse when a sudden loss of generation causes a deviation of frequency, UFLS acts before the full action of UFGC because of the quick drop of frequency.

The application of D-SMES can coordinate the UFGC and UFLS to achieve the goal of full activating the spinning reserve and minimizing shedding load. The reason for using the D-SMES rather than the one concentrated SMES is to coordinate with UFGC locally.

In this paper, the authors studied the coordination of UFLS and UFGC by application of D-SMES. The active and reactive power controls of D-SMES are independent. The active power is controlled to stop the dropping of system frequency and the reactive power is control to stabilize the local voltage.

The research results show that D-SMES can slow the quick drop of system frequency and hold for the full activation of system spinning reserve. That can help the governors output their maximum reserve before UFLS drops more load which results in minimized load shedding.

The authors use a 23 buses sample system in this study. For the bulk power system, the coordination of UFLS and UFGC by application of D-SMES will be more complicated which will be the future research task.

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VII. Biographies

Li Zhang is a visiting scientist and Ph.D. candidate of the Electrical Engineering Department of Virginia Tech. He received B.S degree from the Northeastern University, M.S. degree from the Harbin Polytechnic University, Ph.D. degree from Tsinghua University, P.R. China. Currently, he is in charge of power system and power electronics application research at ECE Department of Virginia Tech, USA. From 1997 to 2001, he was with the Beijing Power Supply Company as an engineer. From May 2001 to October 2001, he was a research fellow in the Building Service Engineering Department of Hong Kong Polytechnic University. He is the main contributor for several National Science Foundation (NSF) projects. His current research interests are power system analysis, power system stability control, power system planning, power electronics, FACTS, energy storage system, and Internet applications in power systems. His E-mail address is zhangli@vt.edu.

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