Battery Energy Storage for Frequency Control

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***Abstract*—Power system frequency depends on the balance between generation and load. And this balance should be maintained constant. Traditionally thermal generators perform the majority of the frequency regulation on the system. However these increases wear on thermal generators and also decrease efficiency. By using Battery energy storage system (BES) to overcome above disadvantage. Battery energy storage technologies have many characteristics which make them well suited to the provision of frequency regulation, reducing peak deviation of frequency and also reduce the steady state values of time error. The main objective of this work is to design a controller for improving both steady state and transient response of a single area load frequency controller with BES.**

Keywords—Load frequency control, Battery energy storage system,

1.INTRODUCTION

A lot of work reported in the literatures to improve the performance of load frequency control (LFC) [1].One alternative method to improve the LFC by using BES. BES have additional benefits as load following, spinning reserve, power factor correction and peak-shaving. BES also improves the reliability of supply during peak loads. Some of these applications have been successfully demonstrated at a 17 MW BES facility in Berlin [2]. Kottick et al. [3] have studied the effect of a 30MW battery on the frequency regulation in the Israeli isolated power system. Their study was single area load frequency model first order system represented the BES performance.S.K.Aditya, D.Das [4] have studied an incremental BES model for two area interconnected reheat thermal system. However, they have not considered the battery state of charge (SOC), grid connected inverter controlling performance, and filter design [5], [6].

In this paper design a controller for controlling the battery energy storage system for single area load frequency controller at different loads. Such as 0.5%, 1%, and 2% incremental loads for an overall capacity 1000MW power. And the battery capacity of plant is 30MW. And design an inverter for controlling the battery energy storage system. The results show that with the use of BES, the performance of LFC can reduces the peak deviations and settling time.

2. SINGLE AREA LOAD FREQUENCY CONTROLLER

The block diagram of single area load frequency controller shown in Figure 1. Here change in load is ΔP_L; change in frequency is Δf; R is speed regulation; and T_g, T_t, T_r, T_p stands time constant of governor, turbine, reheat and power system respectively. The relation between time constants are $T_p > T_t > T_g$. [1] Here the load varies 0.5%, 1%, and 2%.

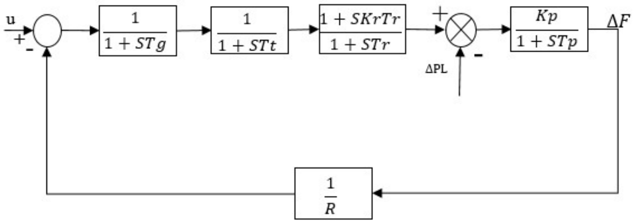

Fig. 1.Block diagram of single area LFC without BES

3. BES MODEL FOR SINGLE AREA LFC

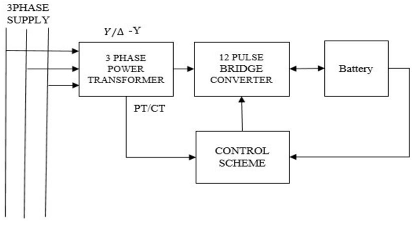

Fig. 2. Schematic description of a BES plant.

A 12 pulse cascade bridge circuit transformer connection is Y/Δ – Y and a control scheme as Shown in Fig.2. The maximum ideal no load voltage (E_{do}) of 12 pulse converter is [2]

$$E_{do} = E_{do1} + E_{do2} = \frac{6\sqrt{6}}{\pi} Et \qquad (1)$$

Where Et is r.m.s phase voltage

The equivalent circuit of the BES shown in Fig. 3.Here the BES charge/discharge through converter. And the E_{boc} is battery open circuit voltage

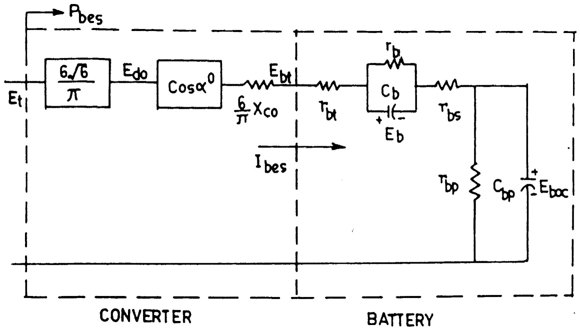

Fig. 3 Equivalent circuit of BES

The terminal voltage of battery is Ebt.

$$E_{bt} = E_{do} \cos\alpha - R_c I_{bes}$$

$$E_{bt} = \frac{3\sqrt{6}}{\pi} E_t (\cos\alpha_1 + \cos\alpha_2) - \frac{6}{\pi} X_{co} I_{bes} \qquad (2)$$

E_b is battery over voltage; r_{bt} is connecting resistance; r_{bs} internal resistance; α is firing angle; I_{bes} is current flowing into battery; X_{co} is commutating reactance; r_b denotes overvoltage resistance; c_b denotes overvoltage capacitance; r_{bp} is self-discharge resistance; c_{bp} is battery capacitance; E_{co} is dc without overlap voltage.

From equivalent circuit of BES (Fig. 3), I_{bes} is

$$I_{bes} = \frac{(E_{bt} - E_{boc} - E_b)}{r_{bt} + r_{bs}} \qquad (3)$$

The converter circuit active and reactive powers are

$$P_{bes} = \frac{3\sqrt{6}}{\pi} E_t I_{bes} (\cos\alpha_1 + \cos\alpha_2)$$

$$Q_{bes} = \frac{3\sqrt{6}}{\pi} E_t I_{bes} (\sin\alpha_1 + \sin\alpha_2) \qquad (4)$$

Where the load frequency control depends on active power only. For active power $\alpha_1 = -\alpha_2 = \alpha$, so the P_{bes} is

$$P_{bes} = \frac{6\sqrt{6}}{\pi} E_t I_{bes} (\cos\alpha)$$

$$P_{bes} = (E_{do} \cos_{\alpha}) I_{bes} \qquad (5)$$

Let us assume,

$$E_{co} = E_{do} \cos\alpha \qquad (6)$$

From Eqs. (4) and (5) we get,

$$P_{bes} = E_{co} I_{bes} \qquad (7)$$

Linearizing Eq. (7), we get the incremental BES power as,

$$\Delta P_{bes} = E^0{}_{co} \Delta I_{bes} + I^0{}_{bes} \Delta E_{co} \qquad (8)$$

The BES operating in constant current mode, but in LFC we adjust the firing angle α. Let us decompose ΔE_{co} into 2 parts, that is

$$\Delta E_{co} = \Delta E_p + \Delta_{Ed} \qquad (9)$$

From Eqs. (8) and (9) we get,

$$\Delta P_{bes} = E^0 co \Delta I_{bes} + I^0{}_{bes} \Delta E_p + I^0{}_{bes} \Delta E_d \tag{10}$$

In above Eq. the second term is to compensate the power deviation caused by ΔI_{bes} and third term is to respond the system disturbance. Therefore, we assume,

$$E^0 C0 \Delta I_{bes} + I^0{}_{bes} \Delta E_p = 0$$

$$\therefore \Delta EP = -\frac{E^0{}_{co}}{I^0{}_{bes}} \Delta I_{bes} = -\frac{E_{do} \cos\alpha}{I^0{}_{bes}} \Delta I_{bes} \tag{11}$$

From Eqs. (10) and (11) we get,

$$\Delta P_{bes} = I^0{}_{bes} \Delta E_d \tag{12}$$

Then the damping signal of battery is $\Delta E_{d\ \mathrm{is}}$

$$\Delta E_d = \frac{K_{bes}}{1 + ST_{bes}} \Delta Signal \tag{13}$$

Where K_{bes} and T_{bes} are control loop gain and time constant, respectively; the Δsignal is power system feedback to provide damping effect.

In general the battery discharge when the converter act as inverter. So the P_{bes} is

$$P_{bes} = \frac{6\sqrt{6}}{\pi} E_t I_{bes} \cos\beta, (\beta = \pi - \alpha)$$

$$\therefore P_{bes} = -E_{do} I_{bes} \cos\alpha = -E_{co} I_{bes} \tag{14}$$

$$\Delta P_{bes} = -I^0{}_{bes} \Delta E_d \tag{15}$$

In general,

$$\Delta P_{bes} = (\pm) I^0{}_{bes} \Delta E_d \tag{16}$$

When sign +ve, battery should be charge, when sign –ve the battery should be discharge.

Then the overvoltage capacitive current (I_{cb}) is

$$I_{cb} = C_b \frac{d}{dt}(E_b) \tag{17}$$

If any deviation occur in battery, then the battery overvoltage capacitive current (Icb) and voltage (E_b) will also deviate from their initial values.

$$\therefore I_{cb} = I^0{}_{cb} + \Delta I_{cb} \tag{18}$$

And

$$E_b = E_b^0 + \Delta E_b \tag{19}$$

From Eqs. (17)- (19) We get,

$$\frac{d}{dt}(\Delta E_b) = \frac{1}{c_b}(I^0{}_{cb} + \Delta I_{cb}) \tag{20}$$

In fig. 2, I_{cb} is

$$I_{cb} = \frac{r_b}{(r_b + X_{cb})} I_{bes} \tag{21}$$

$$I^0{}_{cb} = \frac{r_b}{(r_b + X_{cb})} I^0{}_{bes} \tag{22}$$

And equation 21 re written as

$$\Delta I_{cb} = \frac{r_b}{(r_b + X_{cb})} \Delta I_{bes} \tag{23}$$

From Eqs. (20), (22) and (23), we get,

$$\frac{d}{dt}(\Delta E_b) = \frac{1}{c_b}\frac{r_b}{(r_b + X_{cb})}(\Delta I_{bes} + I^0_{bes}) \tag{24}$$

Then ΔE_b is

$$\Delta E_b = \frac{rb}{(1+ST_b)}(\Delta I_{bes} + I^0_{bes}) \tag{25}$$

Similarly, we obtain,

$$\Delta E_{boc} = \frac{rbp}{(1+ST_{bp})}(\Delta I_{bes} + I^0_{bes})\,. \tag{26}$$

Where,

$$T_b = r_b c_b$$

$$T_{bp} = r_{bp} c_{bp}$$

Then the ΔI_{bes} is

$$\Delta I_{bes} = \frac{\Delta E_{bt} - \Delta E_b - \Delta E_{boc}}{(r_{bt} + r_{bs})} \tag{27}$$

Now using all above Eqs. Incremental block diagram is drawn in Fig. 4[4]

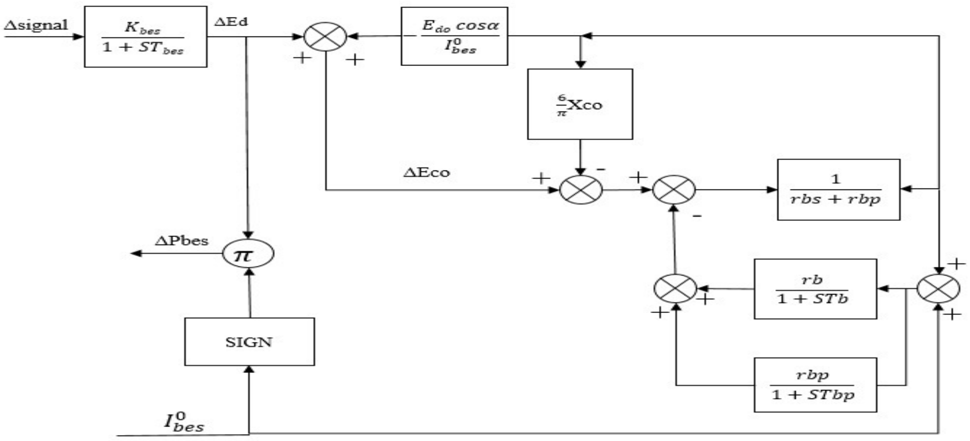

Fig. 4 Block diagram of incremental BES model

TABLE 1

BATTERY PARAMETERS

S.NO	PARAMETERS	VALUES
1	Nominal voltage	400V
2	Rated capacity	30MW
3	Initial state of charge(SOC)	50%

4. INVERTER DESIGING FOR CONTROLLING BATTERY

The Bi-directional converter is to allow the battery to get charged/discharged If the AC power coming from the source is greater than the predetermined value that has to be injected to grid, then battery gets charged through Bi-directional converter and if the generated output is less than the predetermined value, then the battery discharged. The block diagram of grid connected inverter shown in fig 4. [5] The pulse width modulation inverter connected to grid through filter and filter design. [6] We see from the figure that the inverter has 2 PI controllers to compensate the current vector components that are defined from synchronous reference frame (dq).

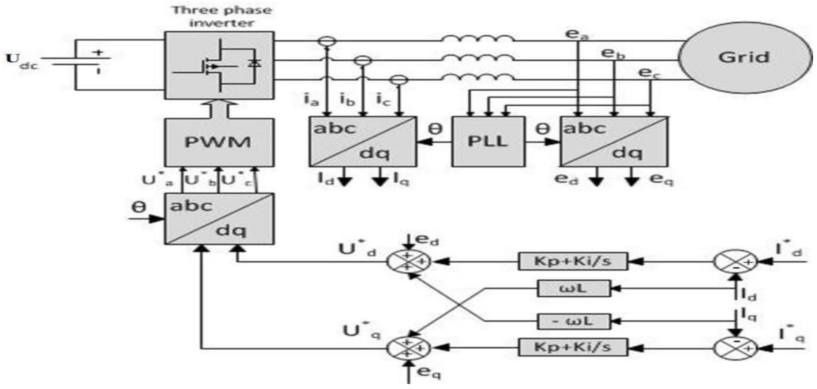

Fig. 5 Block diagram of grid connected converter with control block

TABLE 2

CONTROLLER DESIGN PARAMETERS

S.NO	PARAMETERS	VALUES
1	Battery voltage	400V
2	**LCL filter parameters**	
	Inverter side inductor	2.844e-3H
	Grid side inductor	3.263e-5H
	Capacitor	1.729E-5F
3	**Current control parameters**	
	I_d	1pu
	I_q	0
	Integral constant(K_i)	1.318
	Proportional gain(K_p)	1.88
4	PWM magnitude index	0.8
5	**Phase locked loop parameters**	
	Frequency	60Hz
	Integral constant(K_i)	0.1
	Proportional gain(K_p)	75

Here the LCL filter [6] used for filtering the inverter output voltage and current. The fundamental line to neutral inverter voltage is

$$Vph = \frac{MV}{2} \qquad (28)$$

Where M is PWM inverter modulation index; and V is nominal battery voltage.

5.DEMONSTRATE PRIMARY FREQUENCY CONTROL THROUGH BATTERY ENERGY STORAGE

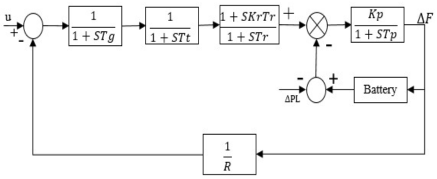

Fig. 6 Block diagram of single area LFC with BES

Fig. 6 shows battery energy storage added to single area load frequency control. Battery energy storage system will operate in discharge mode during peak load period and will be in charging mode during off peak hours. In LFC BES discharging mode is examined.

6. SIMULATION RESULTS

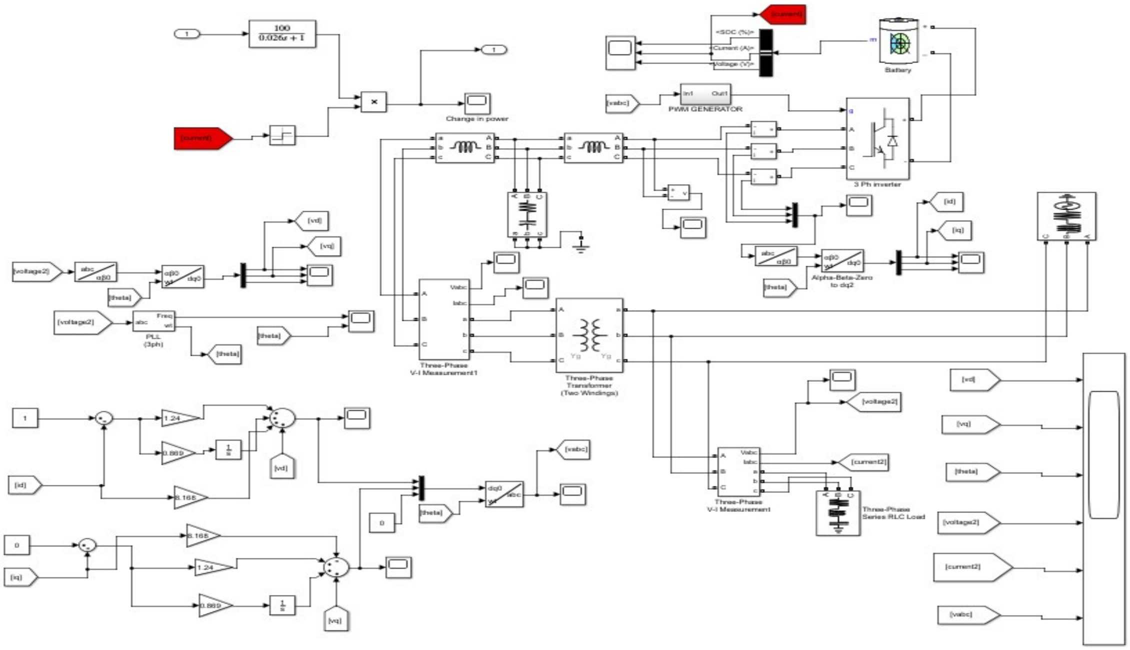

Fig. 7 Simulation block diagram of BES with inverter

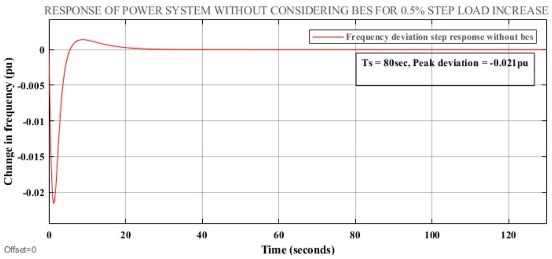

Fig. 8. Response of power system 0.5% step load increases without considering BES

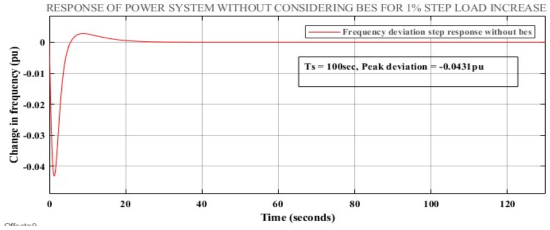

Fig. 9. Response of power system 1% step load increases without considering BES

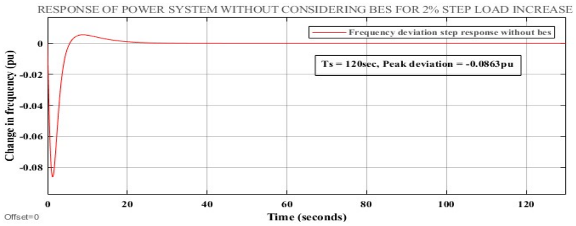

Fig. 10. Response of power system 2% step load increases without considering BES

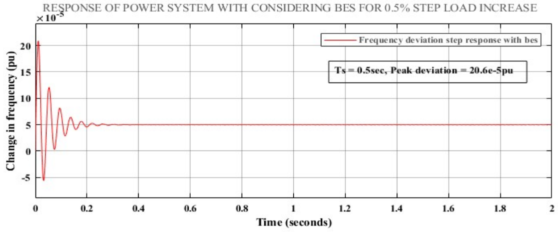

Fig. 11. Response of power system 0.5% step load increases with considering BES

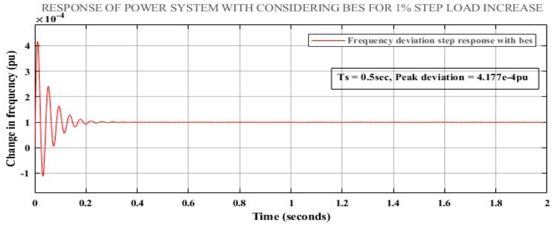

Fig. 12. Response of power system 1% step load increases with considering BES

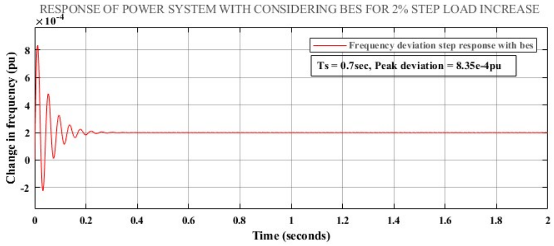

Fig. 13. Response of power system 2% step load increases with considering BES

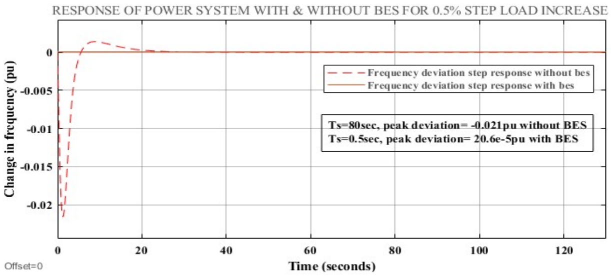

Fig. 14. Response of power system 0.5% step load increases with and without BES

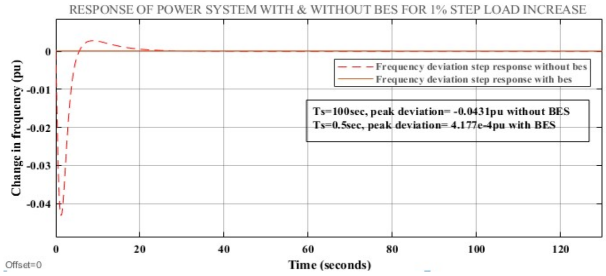

Fig. 15. Response of power system 1% step load increases with and without BES

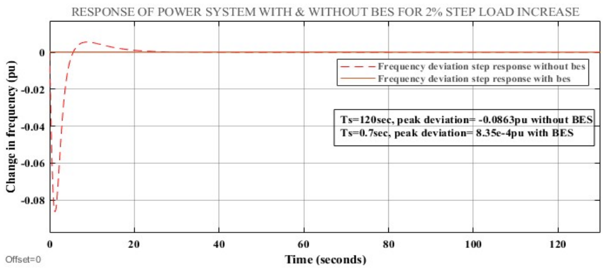

Fig. 16. Response of power system 2% step load increases with and without BES

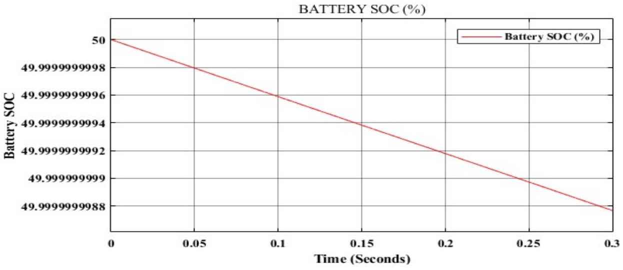

Fig. 17. Battery state of charge

Fig. 8, Fig. 9, and Fig. 10 shows the simulation output of 0.5%, 1%, & 2% load change without considering battery energy storage system, and Fig. 11, Fig. 12, and Fig. 13 shows simulation output of 0.5%, 1%, & 2% load change with considering battery energy storage system. Fig. 14, Fig. 15, and Fig. 16 are comparison of with and without battery energy storage system. By observing the Fig. 14, Fig. 15, and Fig. 16 the BES system capable to reducing the peak deviations and settling time. The Fig.17 shows battery SOC.

I. 7.CONCLUSIONS

A controller for single area load frequency with BES is designed in this work. The BES system reduces frequency deviations resulting from sudden demand variations. The following Table gives the performance of single area load frequency controller with and without BES.

S.NO	PARAMETERS	%LOAD INCREASES	WITHOUTBES	WITH BES
1	Settling time	0.5%(5MW)	80 sec	0.5 sec
2		1%(10MW)	100 sec	0.5 sec
3		2%(20MW)	120 sec	0.7 sec
4	Peak deviation	0.5%(5MW)	-1.26 Hz/ -0.021pu	0.012Hz/ 20.5e-5pu
5		1%(10MW)	-2.586 Hz/ -0.431pu	0.025Hz/ 4.177e-4pu
6		2%(20MW)	-5.178 Hz/ -0.0863pu	0.0501Hz/ 8.35e-4pu

Based on above results, battery energy storage can be uses for providing frequency support in both transient and steady state condition for a given set of controller parameters.

7. APPENDIX

Data for power system
f=60 Hz, P_r=1000 MW, K_p=120 Hz/pu MW, T_p=20.0 s, K_r=0.5, T_r=10.0 s, T_g=0.08 s, T_t=0.3 s, R_1=2.4 Hz/pu MW,
BES (3
Battery voltage=400V d.c., c_{bp}=52597 F, rbp=10 kΩ, c_b=1F, r_b=0.001Ω, r_{bt}=0.0167 Ω, r_{bs}=0.013 Ω, X_{co}=0.0274 Ω, I^{o}_{bes}=4.426 kA, K_{bes}=100 kV/pu MW, T_{bes}=0.026 s,
α=15°.

8. REFERENCES

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