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Superconducting Magnetic Energy Storage System (SMES) Based DVR Battery

Gamidi Divya Rathana Santhoshi (Research Scholar) [1],
G V Rammohan (Assistant Professor) [2]
Department of electrical and electronics engineering, Kakinada Institute of Engineering and Technology-II, A.P

Abstract

This study examines the use of superconducting magneticand battery hybrid energy storage to compensate grid voltage fluctuations. The superconducting magnetic energy storage system(SMES) has been emulated by a high-current inductor to investigate system employing both SMES and battery energy storageexperimentally.

The design of the laboratory prototype is describedin detail, which consists of a series-connected three phase voltagesource inverter used to regulate ac voltage, and two bidirectionaldc/dc converters used to control energy storage system charge anddischarge. “DC bus level signaling” and “voltage droop control”have been used to automatically control power from the magneticenergy storage system during short-duration, high-power voltage sags,while the battery is used to provide power during longer term,low-power undervoltages.

Energy storage system hybridization isshown to be advantageous by reducing battery peak power demandcompared with a battery-only system, and by improving long-termvoltage support Capability compared with an SMES-only system.Consequently, the SMES/battery hybrid dynamic voltage restorercan support both short-term high-power voltage sags and long-termunder voltages with significantly reduced superconductingmaterial cost compared with an SMES-based system.

Index Terms—Battery, dynamic voltage restorer (DVR), energy storage integration, sag, superconducting magnetic energy storage.

I. INTRODUCTION

The improvement of power quality is a significant goal for electrical utilities and modern and business customers. Exceptionally irregular dispersed age, quickly evolving loads, and direct-disconnected power electronic frameworks all add to decreased power quality causing gear personal time, over-burden and disappointment prompting lost income [1].

Voltage unsettling influence is a typical issue and under-voltage conditions have been believed to happen more as often as possible than overvoltage conditions [2]. Present moment under-voltage lists are characterized in IEEE Std. 1159-1995 [3] as a reduction to somewhere in the range of 0.1 and 0.9 p.u.

(per unit) r.m.s voltage for terms of 0.5 cycles to 1 min.

They happen more much of the times than long haul under-voltages with noteworthy expenses to industry [4]. Long haul under-voltage occasions are characterized as a deliberate voltage under 0.8-0.9 p.u. r.m.s voltage, enduring longer than one moment [3] and can prompt burden shedding and possibly to voltage breakdown [5]. The investigation beneath presents a methods by which both present moment and long haul voltage changes can be relieved at the heap utilizing momentary attractive energy storage and long haul battery energy storage.

II. LITERATURE REVIEW

Techniques to relieve long haul voltage aggravation, for example, load disengagement [6] or alteration of burdens for more noteworthy low-voltage ride-through ability might be unreasonable [7]. On the other hand, flexibly voltage can be balanced out by tap evolving transformers, uninterruptable power supplies (UPS), shunt connected compensators, or dynamic voltage restorer (DVR) frameworks. DVR frameworks can act naturally supporting by utilizing power from the matrix to moderate unsettling influences [9]. On the other hand, DVR frameworks can utilize energy storage to give power during pay, for example, capacitors [10] for momentary storage or batteries [11] for longer-term storage. Nielsen and Blaabjerg [12] have indicated that capacitor-bolstered DVR frameworks can experience the ill effects of generally terrible showing for extreme and long term lists. An ongoing report has demonstrated that a ultra-capacitor based DVR [13] can be utilized to alleviate transient voltage lists enduring short of what one moment.

Wang and Venkataramanan [14] have indicated that flywheels are a reasonable momentary energy storage innovation for use with voltage restorer frameworks both tentatively and by reproduction. Kim et al. [15] have portrayed a 3 MJ/750 kVA SMES-based DVR framework and indicated exploratory outcomes affirming that SMES is reasonable for the pay of transient voltage lists. Shi et al. [16] have utilized a framework level Simulation to likewise show that SMES energy storage is equipped for repaying voltage lists enduring 100ms.

III. Dynamic Voltage Restorer (DVR)

Voltageswells are not as significant as voltage hangs since they are more uncommon in dissemination frameworks. Voltage hang and swell can cause delicate gear, (for example, found in semiconductor or synthetic plants) to fall flat, or shutdown, just as make an enormous current unbalance that could blow circuits or outing breakers. These impacts czn be extravagant for the client, extending from minor quality varieties to creation personal time and equipment harm.

Types of gear utilized in current mechanical plants, for example, process regulators, plc's, flexible speed drives,and robots, turns out to be more delicate to voltage droops as the multifaceted nature of the hardware increments. Transfers and contactors in engine starters are touchy to voltage lists, bringing about personal time when they drop out.

It is essential to segregate singular bits of hardware that appear to be more delicate to voltage hangs and to figure out where to send droop remedy gadgets. Area can assume a job in a machine's voltage hang affectability. Additionally, wiring is now and again to fault, and expanding wire size can decrease voltage drop. Droop revision gadgets can be applied at different areas, including the control board, machine level,bus level,or even at the plant administration entrance.

A Dynamic Voltage Restorer (DVR) is an arrangement associated strong state gadget that infuses voltage into the framework so as to direct the heap side voltage. The DVR was first introduced in 1996. It is ordinarily introduced in a dispersion framework between the gracefully and the basic burden feeder. Its essential capacity is to quickly support up the heap side voltage in case of an unsettling influence so as to maintain a strategic distance from any power disturbance to that heap.

There are different circuit geographies and control plots that can be utilized to actualize a DVR. Notwithstanding voltage hangs and swells remuneration, DVR can likewise include different highlights, for example, line voltage sounds pay, decrease of homeless people in voltage and flaw current confinements.

The Dynamic Voltage Restorer (DVR), Fig 4.3, is intended to alleviate voltage droops on lines taking care of touchy gear. A practical option in contrast to uninterruptible power frameworks (UPS's) and other use voltage answers for the voltage droop issue, the DVR is explicitly intended for enormous burdens (2 MVA and up) served at conveyance voltage. A DVR is expected to be a lower cost alternative to UPS for applications at distribution voltage. A DVR typically requires less than one-third the nominal power rating of the UPS. Also, the DVR can be used to mitigate troublesome harmonic voltages on the distribution system. The DVR is available in 2 MVA increment sizes up to 10 MVA.

The majority of voltage sags are within 40% of the nominal voltage. Therefore, by designing drives and other critical loads, capable of riding through sags, with magnitude of up to 40%, interruption of processes can be reduced significantly. The DVR can correct sags resulting from faults in either the transmission or the distribution system.

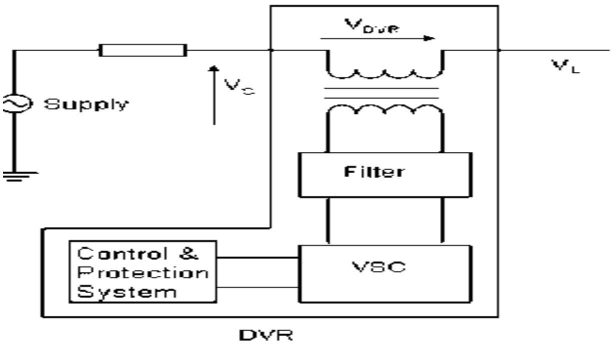


Fig. 1 Block diagram of DVR system

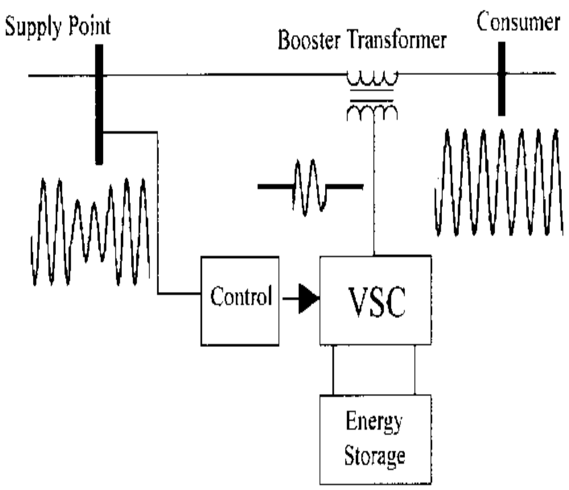


Fig. 2Schematic diagram of DVR System

IV.Function of DVR

The principle capacity of a DVR is the assurance of touchy burdens from voltage droops/swells originating from the system. Hence as appeared in Figure4.1, the DVR is situated on approach of delicate burdens. On the off chance that a deficiency happens on different lines, DVR embeds arrangement voltage VDVR and compensates load voltage to pre shortcoming esteem.

The transient amplitudes of the three infused stage voltages are controlled, for example, to take out any hindering impacts of a transport deficiency to the heap voltage VL. This implies any differential voltages brought about by transient aggravations in the air conditioner feeder will be repaid by a proportional voltage produced by the converter and infused on the medium voltage level through the booster transformer.

The DVR works autonomously of the kind of deficiency or any occasion that occurs in the framework, given that the entire framework stays associated with the gracefully lattice, for example the line breaker doesn't trip. For most viable cases, a more conservative structure can be accomplished by just remunerating the positive and negative grouping parts of the voltage unsettling influence seen at the contribution of the DVR. This choice is Reasonable on the grounds that for a commonplace circulation transport arrangement, the zero grouping some portion of an unsettling influence won't go through the progression down transformer in light of interminable impedance for this part.

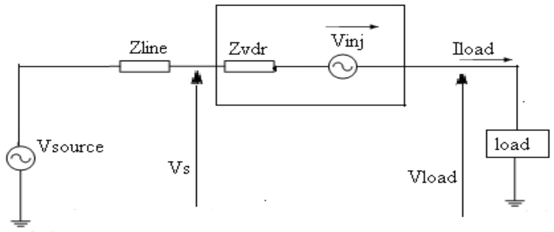


Fig3: Equivalent Circuit of DVR

Figure 3 shows the equivalent circuit of the DVR, when the source voltage is drop or increase, the DVR injects a series voltage Vinj through the injection transformer so that the desired load voltage magnitude VL can be maintained. Theseries injected voltage of the DVR can be written as Vinj = Vload + VsWhere as **VinjLoad** is the desired load voltage magnitude, **Vs** is the source voltage during sags/swells condition and the load current **ILoad** is given by

$$I_{load} = \left(\frac{P_{Load} \pm J * Q_{Load}}{V_{Load}} \right)$$

V. Simulation of DVR

To evaluate voltage hang in spiral circulation framework, the voltage divider model, appeared in Fig. 3, can be utilized on the suspicion that the shortcoming current is a lot bigger than the heap current during deficiencies. The purpose of regular coupling (PCC) is the point from which both the issue and the heap are taken care of. Voltage droop is generally uneven and joined by stage point bounce.

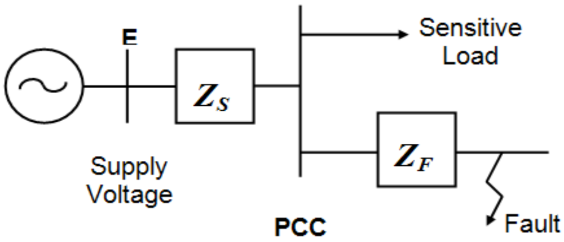


Fig.4 Voltage divider model for Voltage Sag.

$$V_{\text{sag}} = \frac{Z_F}{Z_S + Z_F} E = \frac{Z_F}{Z_S + Z_F}$$

$$\Delta\phi = \arg(\bar{V}_{\text{sag}}) = \arctan\left(\frac{X_F}{R_F}\right) - \arctan\left(\frac{X_S + X_F}{R_S + R_F}\right)$$

$$\begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \qquad (1)$$

$$\begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} = \begin{bmatrix} \cos\theta_{\text{pll}} & \sin\theta_{\text{pll}} \\ -\sin\theta_{\text{pll}} & \cos\theta_{\text{pll}} \end{bmatrix} \begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix} \qquad (2)$$

WhereVsa, *b*, *c*,Vs α , β ,Vsd, *q*are the supply voltages and θpll is theestimated supply phase angle.

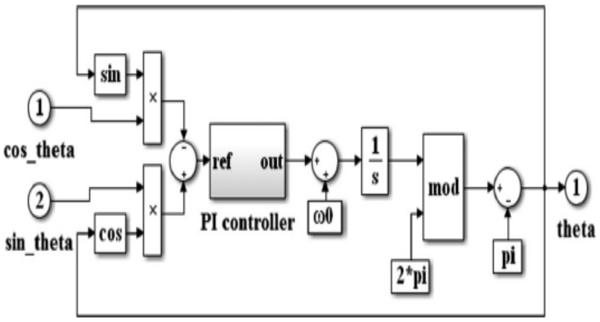


Fig. 5 Simulink implementation of PLL algorithm where $\omega 0$ is the fundamental output frequency in rad/s.

A stage bolted circle (PLL) was utilized to decide the stage edge θpll of the approaching gracefully dependent on a calculation which is strong within the sight of harmonics, non-evenness and drifters [23]. Fig. 3 shows a Simulink execution of the PLL calculation.

This calculation limits the sine of the stage blunder term making the control framework be non-direct. Thus, the PI regulator gains were tuned observationally. The PLL calculation requires the cosine and sine of the approaching gracefully edge as sources of info which can be gotten mathematically utilizing the symmetrical reference outline voltages from (1) as:

$$\cos(\theta) = \frac{V_{s\alpha}}{\sqrt{V_{s\alpha}^2 + V_{s\beta}^2}} \qquad (3)$$

$$\sin(\theta) = \frac{V_{s\beta}}{\sqrt{V_{s\alpha}^2 + V_{s\beta}^2}} \qquad (4)$$

The PLL regulator can be tuned to protect the period of the approaching gracefully before a list occasion with stage hop or, on the other hand, the PLL can be made to follow the period of the approaching flexibly during a droop with stage bounce. Therefore, by changing the PLL picks up the framework can be controlled to give 'in stage' or 'pre-hang' pay. Fig. 4 delineates the consequences of tuning the PI regulator along these lines. To identify the nearness of a voltage mistake, the accompanying imbalance was utilized [24], [25]:

$$\sqrt{\left(V*_d - V_{s,d}\right)^2 + \left(V*_q - V_{s,q}\right)^2} \geq V_{\text{threshold}} \qquad (5)$$

Where*Vsd*, *q*is the measured load voltage and *V *d,q*is thedesired nominal voltage in the synchronous reference frame.Inequality (5) was also used to trigger the disconnection of theDC bus auxiliary power supply (see Fig. 1).

The compensation voltage *V*ref *d,q*is determined, based onthe error between the desired nominal voltage and the supplyvoltage:

$$V_{\text{ref}\,d,q} = V*_{d,q} - V_{d,q} \qquad (6)$$

The PWM phase reference voltages *V*ref *a,b,c*were generatedby transforming the required compensation voltage to the

$$\begin{bmatrix} V_{\text{ref}\alpha} \\ V_{\text{ref}\beta} \end{bmatrix} = \begin{bmatrix} \cos\theta_{\text{pll}} & -\sin\theta_{\text{pll}} \\ \sin\theta_{\text{pll}} & \cos\theta_{\text{pll}} \end{bmatrix} \begin{bmatrix} V_{\text{ref}}d \\ V_{\text{refq}} \end{bmatrix} \qquad (7)$$

$$\begin{bmatrix} V_{\text{ref}}a \\ V_{\text{ref}}b \\ V_{\text{ref}}c \end{bmatrix} = k\frac{3}{2} \begin{bmatrix} 2/3 & 0 \\ -1/3 & 1/\sqrt{3} \\ -1/3 & -1/\sqrt{3} \end{bmatrix} \begin{bmatrix} V_{\text{ref}\alpha} \\ V_{\text{ref}\beta} \end{bmatrix} \qquad (8)$$

The injection voltages, *V*ref *a,b,c*, were multiplied by a feedforwardconstant, *k* to compensate for losses within the powerstage.The current droop characteristic for each device is shownin Fig. 5, and is made up of three regions of operation. Whenthe DC voltage is above voltage level *Vh*(*x*) (where *x* refersto energy storage system 1 or 2) or below *Vl*(*x*),, theconverter current is limited to *I*max(*x*) or -*I*max(*x*) . In between*Vh*(*x*) and *Vl*(*x*) , current is controlled based on the linear currentvs. voltage relationship:

$$I_x = \left(V_{\text{nom}} - V_{\text{bus}}\right) k_x \qquad (9)$$

Where*kx* is a droop coefficient (A/V) and *Ix* is the energystorage converter reference current.The relationship between DC bus current,inductor current and duty ratio, is given by (12) and (13) for

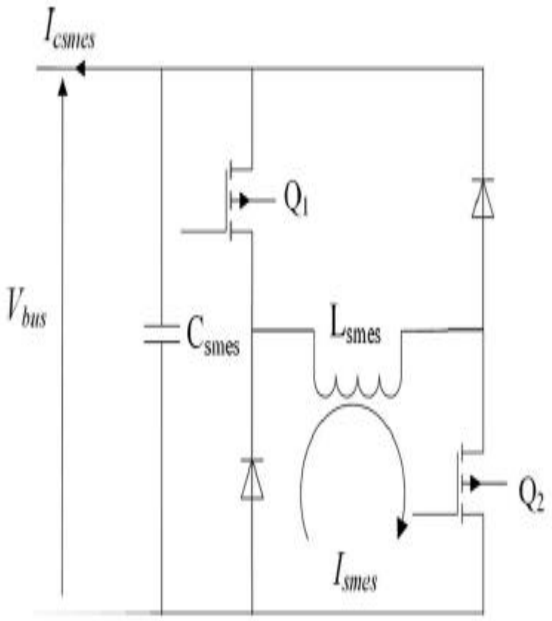


Fig. 6. SMES DC/DC converter.

Charge and discharge, respectively [16].

$$I_{csmes} = I_{smes} D_1 \qquad (10)$$

$$-I_{csmes} = I_{smes}(1 - D_2) \qquad (11)$$

For active current droop control according to (9), the desiredconverter output current *Icsmes* is given by (12).

$$I_{csmes} = \left(V_{bus} - V_{nom\_smes}\right) k_{smes} \qquad (12)$$

Where*k*smes is the gradient of the droop controller and *V*nom smesis the nominal voltage of the droop controller.The proposed techniqueis shown below to be globally stable over the operating rangewhereas typical current mode control techniques described previously [13] require slope compensation to ensure global stability[28]. Further advantages include good dynamic current trackingcapability, and robust performance despite variationand uncertainty in operating conditions [29].

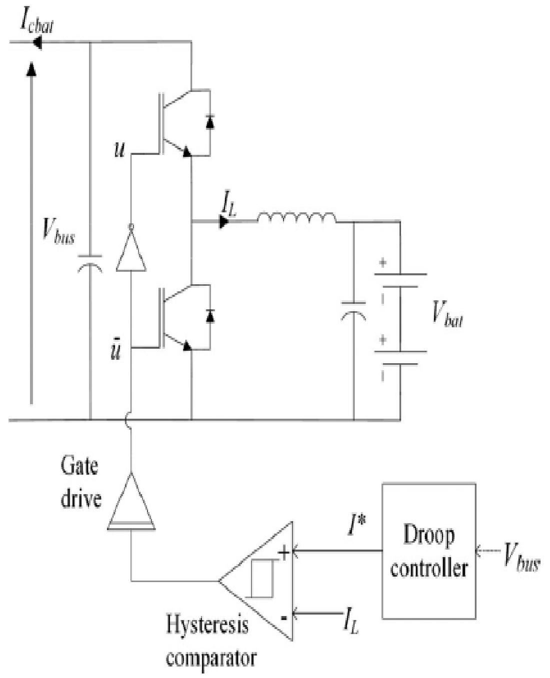


Fig. 7. Battery DC/DC converter.

Assuming lossless, ideal components, the inductor current inFig. 7 is given by (13).

$$L\frac{dI_L}{dt} = V_{\text{bus}}u - V_{\text{bat}}\bar{u} \qquad (1$$

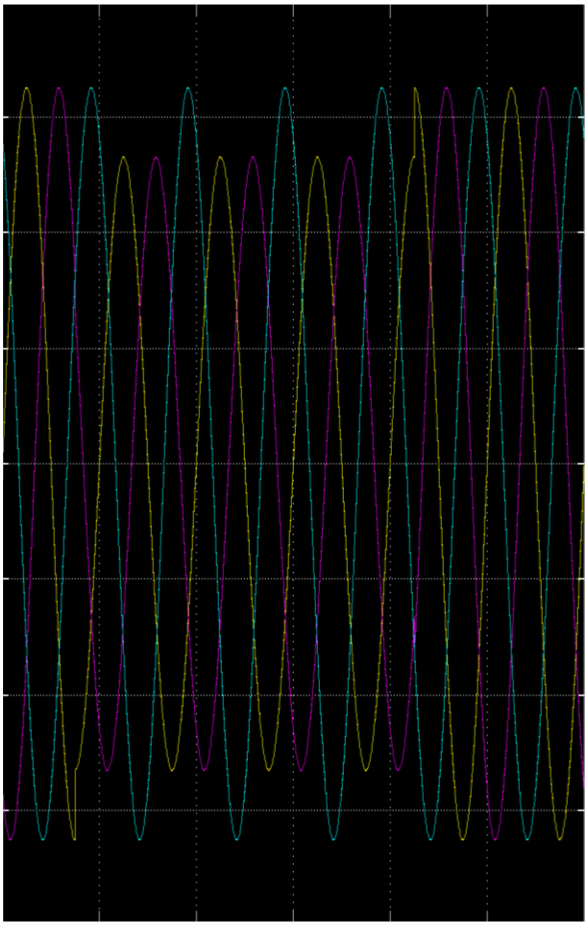
Where*u* is a gate drive signal and *V*bat and *V*bus are battery andDC bus voltages. Sliding-mode control theory may be used to describe thecurrent regulation strategy [30]. The objective in this case isto regulate the inductor *IL* , such that it tracks the commandreference current $I*$. A function $\sigma = 0$ can be defined as follows [30]:

$$\sigma = I_L - I* \qquad (14)$$

VI. RESULTS

Initially a three-phase voltage sag to 35% of nominal voltage, lasting 100 ms was used to demonstrate the response of theDVR and energy storage systems. From Fig. 10 it can be seen that the hybrid DVR system mitigates the voltage sag effectivelyduring the sag event. The battery is discharged momentarily at −1.45 A at the end of the sag when the inductor energy has beendepleted.

The SMES-emulator was then removed from the system andthe test was repeated. The system response to the same three phase sag with only battery energy storage is shown in below Fig.As the DC bus voltage falls below 140 Vdc (the battery systemnominal voltage) the battery is discharged to support the DCbus. The peak battery current is 21.13 A in this case and theDVR system can be seen to effectively mitigate the voltage is shown in below Fig.



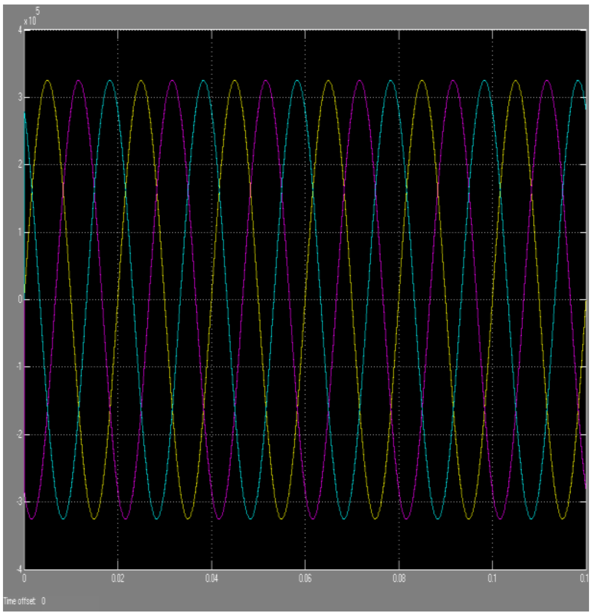


Fig.8. Hybrid System Experimental results: 0.1s Three phase sag to 35%of nominal voltage. (a) Supply voltages. (b) Load voltages

VII. CONCLUSION

The performance a novel hybrid DVR system topology has been assessed experimentally and shown to effectively provide voltage compensation for short-term sags and long-term under-voltages. A prototype system has been developed whichdemonstrates an effective method of interfacing SMES and batteryenergy storage systems to support a three phase load. Thesystem has been shown to autonomously prioritise the use ofthe short-term energy storage system to support the load duringdeep, short-term voltage sags and a battery for lower depth,

Long-term under-voltages. This can have benefits in terms ofimproved voltage support capability and reduced costs comparedwith a SMES-based system. Additional benefits include reduced battery power rating requirement and an expected improvement in battery life compared with a battery-only system due to reduced battery power cycling and peak dischargepower.

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