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A Model Predictive Compensator Strategy for Performance Improvement of Hybrid Energy Storage Systems in DC Microgrids

S. RUBEENA BI [1], M.SWATHI [2], S.UME SALMA[3], K.UMA MANASA[4], K.VAMSI KRISHNA[5], K.UDAY KUMAR[6] [1,2]**Assistant professor, Department of Electrical and Electronics Engineering, Annamacharya Institute of Technology and Sciences (AITS), Rajampet.**
[3,4,5,6]**Student of Electrical Engineering, Annamacharya Institute of Technology and Sciences (AITS), Rajampet.**.

ABSTRACT: The most typical method used in DC microgrid(MG)applications for battery-supercapacitor Hybrid Energy Storage Systems(HESSs)is Filtration-Based(FB)power/current allocation. In this method, the input power/current of the HESS is divided into high-frequency and low-frequency components, and the high-frequency components are subsequently assigned to the SC. Additionally, this strategy necessitates a rule-based supervisory controller, which may cause SC to stop functioning, in order to prevent the State of Charge violation(SoC) of SC. In order to study the effects of an FB current allocation system on the dynamic stability of an islanded DCMG in which a grid-forming HESS supplies a Constant Power Load(CPL), this paper first presents a small-signal stability analysis. Then, it demonstrates that the ongoing operation if the grid-forming HESS is loaded by huge CPLs, of SC is crucial. In order to solve this problem, this research suggests a Model Predictive Control (MPC) method that collaborates with a high-pass filter to carry out the battery and SC current assignment. This method ensures the ongoing operation of SC by automatically restoring the SoC of SC after abrupt load changes and limiting its SoC variation in a pre-set range. Indirectly enabling the MG's Proportional-Integral(PI)voltage controller to work with larger gain values, which improves transient response and voltage quality, is the goal of the suggested FB-MPC technique. The system is then simulated in MATLAB/Simulink to validate the performance of the suggested approach.

Index-Terms- Filtration-based power/current allocation systems, battery/supercapacitor hybrid energy storage systems, model predictive control, stability analysis, state of charge recovery.

NOMENCLATURE

A. ABREVIATIONS

BESS	Battery Energy Storage System.
CPL	Constant Power Load.
CPS	Constant Power Source.
DC	Direct Current.
DER	Distributed Energy Resources.
FB	Filtration Based.
HESS	Hybrid Energy Storage System.
HPF	High Pass Filter.
LTI	Linear Time Invariant.
EMS	Energy management system.
MG	MicroGrid.
MPC	Model Predictive Control.
MPPT	Maximum Power Point Tracking.
PPL	Pulsed Power Load.

B.SYMBOLS

d_1	Duty cycle of the BESS converter.
d_2	Duty cycle of the SC converter.
d_{com}	Compensation term added/subtracted to/from the SC/BESS reference current.
i_{CP}	Resultant current of the CPL and CPS.
i_{com}	MPC compensation current.
i_{HESS}	HESS output current.
i_{HPF}	Output current of the high-pass filter.
PV	Photo Voltaic.
SC	Super Capacitor.
SoC	State of Charge.

i_{L1}	InductorcurrentoftheBESS.
i_{L2}	InductorcurrentoftheSC.
i_{Load}	LoadCurrent.
i_{PV}	PVoutputcurrent.
i_{ref}	Reference current of the HESScomputedbythevoltagecontroller.
SoC_{max}	Maximum allowable SoC for SC.
SoC_{min}	Minimum allowable SoC for SC.
SoC_{ref}	ReferenceSoCofthe SC.
SoC_{SC}	SoCoftheSC.
v_b	TerminalvoltageoftheBESS.
v_{ref}	Referencevoltageofthevoltagecontroller
v_{SC}	TerminalvoltageofSC.

I.INTRODUCTION

A. LITERATUREREVIEW

Micro Grids (MGs) are autonomous active distribution networksthatcanimprovetheperformanceofconventionalpowergridsbyboosting customer engagement, penetration of renewable energysources, stability of the power grid, and grid resilience [1], [2].Becausetheyhavelesscontrolcomplexityandfewer powerconversionlossesthanACMGs,DCMGshaverecentlyattractedalotofattention.DCMGscanbeviewedasworkableoptionsforimprovingtheresilienceofpowersystems,electrifyingruralareas, and assisting local energy communities [3]. The existenceof Continuous Power Loads (CPLs) and Pulsed Power Loads(PPLs), which call for a quick dynamic reaction and a substantialstabilitymarginofthecontrolsystem[4]-[6],mightmakecontrolling DC MGs difficult. Highly-dispatchable DistributedEnergy Resources (DERs) as well as other technologies can beused to increase the system's transient response, stability, andflexibility,improvedcontrolandmanagementmethodsareneeded[7].

One of the most common energy storage sources for MGapplicationsareBatteryEnergyStorageSystems(BESSs).BESSs have low energy losses, are dispatchable, and are veryinexpensive. Additionally, they are well suited for peak shavingandsteady-statepowerbalancingduetotheirhighenergydensity[8],[9].Duetotheirlowpowerdensity,theBESSsmay,however,exhibit very poor transient response during rapid load changes[7],[10].As a result, in the presence ofPPLs, grid-formingBESSsmaynot deliversatisfactoryperformance and voltagequality for a DC MG. BESSs also have a constrained lifespan.Therefore, the BESSs lifetime may be shortened byfrequentbatterycharginganddischargingduetotheinstantaneousdifferencesinrenewableenergygenerationorloadpowerfluctuations[10], [11].

A successful combination of Super Capacitors (SCs) andBESSscaneffectivelyaddresstheaforementionedBESSshortcomings[7],[12].TheSCsofferagreaterpowerdensityanda quicker dynamic response than the BESSs. Therefore, they canrelease/absorb more energy for a much shorter period of time.They also have a substantially longer lifecycle than BESSs do.Therefore, the repeated charging and discharging of SCs has noimpact on their lifespan. However, because to their low energydensity,SCsareinappropriateforlong-termenergystorageapplications [13]. Battery-supercapacitor Hybrid Energy StorageSystems (HESSs) combine a BESS and a SC to increase thesystem's dynamic performance and lengthen its lifespan whiletaking into account the structural capabilities and limitations ofeach these BESSs. To do this, the SC absorbs transient powerfluctuations from loads (such as PPLs) or renewable resources(such as PV or wind), while the BESS is utilised for steady-statepower balancing[10].

The active topologies, which are more desirable due totheir better controllability, can be built for HESSs made up of aBESSandSC.Othertopologiesincludepassive,semi-active,andactive topologies. Aside from the active topologies, the entiredispatchcapabilityofBESSandSCcanbeused[11].EachoftheHESScomponents(i.e.,theBESSandSC)inthesetopologieshasa separate current control system and is coupled to the MG DCbus via a power electronic converter to offset the higher expenseof theactivecomponents(suchaspowerelectronicconverters),amoresophisticatedcontrolandEnergyManagementSystem(EMS)should be used[14].

The creation of adequate offline and online managementand control algorithms is necessary for the HESSs to functioneffectively and reliably. To determine the appropriate size of theSC,BESS,andotherDERsusingofflinemethods,variousoptimizationalgorithms(suchasstochasticprogrammingorgenetic algorithms) can be implemented based on the cost of thesystem'sequipment,theamountofpowerthattheloadsarerequesting, the availability of renewable energy sources (such aswind or PV), and the size of the SC, BESS, and other DERs. Onthe other hand, online algorithms are required to guarantee thesystem'sdependablereal-timeperformance.Forvariousobjectives, the MG's various control layers can execute real-timemanagement and control procedures. For instance, they can beusedinthesecondarycontrollayeroftheMGforreal-timepowersharing between the HESS components (i.e., the BESS and SC)and other DERs, or they can be implemented in the tertiary levelof the MG for the best (or most economical) State of Charge(SoC) management of the BESSs. To increase the MG's transientvoltagestabilityandvoltagequality,theycanalsobeincorporatedin the primary control layer for efficient current sharing betweenthe BESS andSC[11].

In DC MG applications, a HESS can function as a grid-forming unit when the DC MG is islanded or as a grid-followingunitwhentheDCMGis connectedtotheutilitygrid.In thegrid-connected mode of the MG, a bidirectional AC to DC converteris used to connect to the superior AC grid and regulate the DCMG's voltage. Since the HESS is in power (or current) controlmode in this instance, its functioning has no effect on the MG'stransient voltage stability. In this working mode, the SC absorbstheinstantaneouspowerfluctuationsandtheEMS(i.e.,thetertiary control layer) of the MG computes a reference power fortheBESSandSC.Inordertoachieveefficientpowerallocation

betweentheHESScomponentsandreducetheoperationalcostofthe MG,real-timeoptimization-basedenergymanagementsolutions can be implemented at the tertiary level of the MG. Toachieve this, real-time optimal EMS techniques often take thesystem's operation over the medium term (i.e., over the course ofa few hours), ignoring the system's rapid dynamics connected toprimary-level controllers and power electronic converters [11],[15].

The HESS module is in charge of preserving the dynamicstability and voltage quality of the DC MG during grid-formingoperation(i.e.,theislandedmodeoftheMG).Inthisinstance,theProportional-Integral(PI)voltagecontrollercomputesareferencecurrent signal, which the HESS receives in order to manage thevoltageoftheMGDCbus.Asaresult,thevoltagecontrollerandcurrentregulatorofthe BESSandSCconverters, aswellasotherprimary-levelcontrollers,mayinterfacewiththeHESSpower/current allocation system. As a result, the system's voltagequality and transient response may be indirectly impacted by theHESS activities.

Thus, in order to efficiently share the HESS referencecurrent calculated by the MG voltage controller between the SCand BESS, the HESS power/current allocation system shouldhave a substantially faster dynamic reaction than grid-followingoperation. [7],[16],[17].

Themostpopularmethod forMGapplicationsthatcanbeusedforgrid-followingandgrid-formingHESSdevicesisFiltration-Based(FB)power/currentallocation.BecauseFBtechniques are computationally simple, they can be used in real-time applications, such as grid-forming HESS units [11], [18].Inthismethod,theHESScontrolsystemdividestheHESSreferencecurrent/powerintohigh-frequencyandlow-frequencycomponentsusingalow-passorhigh-passfilter,andthendistributes the high-frequency parts to SC and the low-frequencypartsto BESS (i.e.,operating mode"BESS-SC").

Because SC has a low energy density and a quick chargetime (a few seconds, for example), it can be fully charged ordischargedrightawayafterafastchangeinload.TheSoCfluctuation of SC (and its terminal voltage) cannot, however, beautomaticallyconstrainedbystandardFBtechniquestoaspecificrange. As a result, they frequently use a rule-based supervisorycontroller that, if the SoC of SC deviates from a specified range,may disable the filter and transfer the HESS reference current tothe BESS (i.e., "BESS-only" operation). In order to keep the SCSoCvariationwithinapredeterminedrange,theHESSmayfrequently switch between several operating modes. As a result,the continuous operation of SC is not guaranteed.The voltagequality of MG may be impacted by these switching instances andtransient voltage variations that may occur when the system isoperating.Additionally,thisarticlelooksattheMGvoltagecontrolsystem's marginalstabilityandcomparesittothe"BESS-only"operationwhenagrid-formingHESSoperatesinthe"BESS-SC" mode. Therefore, it is crucial to ensure the ongoingoperationofSCduetothedestabilisingeffectofCPLs,especiallyif the grid-formingHESS isloadedbya significant CPL.

InordertoensurethatSCoperatescontinuously,inpractise either the size of SC needs to be large enough to handlethe significant power/current variations, which raises the initialcost of the system, or the cut-off frequency of the filter needs tobelowered,whichshortensthelifetimeoftheBESS.Thepreviousresearchoftheauthors[19]aimedtoresolvethisproblem by creating an active compensating filtering techniquethat automatically recovers the SoC (or terminal voltage) of SCin order to drastically lower the necessary number of switchinginstances. To ensure that the SC's SoC variation stays within apredetermined range, that technique still requires a rule-basedEMS that can deactivate the SC. A virtual capacitance drooptechnique that may automatically restore the SoC of SC to areference value is also suggested in the proposed work in [20]. Itis further demonstrated that, provided the droop parameters areproperlychosen,thisstrategycanmarginallyenhancethemarginal stability of MG. One inherent shortcoming of the droopcontrol strategies is that this method may result in a steady-statevoltage deviation [21]. Additionally, selecting the proper droopcoefficientsinDCMGswithnumerousloadsorDERsmightbe

a difficult issue.

Model Predictive Control(MPC) techniques have recently attracted a lot of interest in HESS applications. The main principle of MPC is to compute a series of future control actions to minimise a predefined cost function(i.e., optimization step) by using the dynamical model of the system to predict the system's outputs(i.e., prediction step) within a moving horizon(i.e., prediction horizon) [22], [23] The real-time optimization process of MPC controllers is one of their intriguing aspects. MPC techniques can therefore automatically keep the SoC fluctuation of the HESS components within a given range. However, as compared to rule-based techniques, they have a much larger computational complexity.

The MPC techniques can be used in many control levels for various purposes in DC MGs with HESS technologies. For instance, the references [24]-[28] offer an MPC-based Energy Management System(EMS) for HESSs, in which the MPC controllers are positioned at the tertiary level of the MG and are in charge of scheduling and managing energy usage for various DERs, including the HESS units. The sample time or action time of the MPC controller in these applications is typically in the region of a few minutes. Consequently, the MPC prediction model (i.e., the prediction step) does not take the system's rapid dynamics into account(e.g., primary controllers, power electronic converters, and circuit dynamics). As a result, these techniques don't target the MG's voltage stability or transient responsiveness; instead, they concentrate on enhancing the system's steady state performance. Additionally, the MPC controllers at this layer often have centralised architectures that require knowledge from all DERs to guarantee the efficient operation of MG. As an alternative, the output voltage and currents of the power electronic converters can be controlled using MPC controllers in the primary controller layer of the MG (for example, using direct MPC methods) [22]. For instance, the reference [29] suggests using a Finite Control Set -MPC (FCS-MPC) strategy to increase the grid-forming HESS unit in a DC MG's transient response and resilience. According to this method, the FCS-MPC is positioned at the MG's primary control layer and directly controls the converters' switches to regulate the output current of the BESS and SC to their respective reference values, which are both calculated by an FB power/current allocation system. However, because to their great computational complexity, FCS-MPC techniques could inherently result in unsolvable optimization issues [23]. They also result in variable frequency switching, which affects the output filter design of the converter [30], [31]. Furthermore, their use in DC MG applications necessitates a significant redesign of the inner loop converter controllers, which may not always be possible. The real-time control and management strategies of HESSs are compared in Fig. 1 to the conventional control hierarchy of DCMGs.

B. CONTRIBUTION AND SCOPE

This work makes the following contributions to address the issues raised and enhance the functionality of a grid-forming HESS unit in controlling the MG DC bus voltage(i.e., improving the functionality of the MG primary controller layer):

1) This study presents a comprehensive state-space dynamic model of an islanded DC MG that receives a CPL from a grid-forming HESS. Furthermore, it is anticipated that the HESS has a standard FB supervisory controller and power/current allocation technique.

2) It offers a small-signal stability study to contrast the MG's marginal stability between the HESS's "BESS-SC" and "BESS-only" operating modes. According to the stability analysis, the DCMG exhibits noticeably greater marginal stability when running in the "BESS-SC" mode. This means that the MG PI voltage controller can operate with noticeably higher gain settings and remain stable for longer communication delays if the HESS only executes the "BESS-SC" operating mode.

3) The current assignment between the BESS and SC is performed using a Linear Time-Invariant(LTI) filter and an MPC control system using an FB-MPC strategy. In this method, after abrupt load changes, the MPC module immediately recovers the SoC of SC and makes sure that its SoC variation stays within a

predetermined range. As a result, the grid-forming HESS is able to operate continuously in "BESS-SC" mode, ensuring SC's uninterrupted operation. As a result, the PI voltage controller for the MG may function at greater gain levels, improving the voltage quality and transient response, especially when the DC MG is heavily loaded by large CPLs.

4) The proposed MPC controller is different from other MPC strategies used in DCMG applications in that it interacts with the voltage and current regulators of the power electronic converters but is not in charge of controlling their output voltage or current. Instead, it is situated at the primary control layer of the MG. Instead, by computing a compensation term and adding or removing that value from the reference current of the BESS and SC power electronic converters, it is in charge of controlling the SC SoC fluctuation. It is not necessary for it to be as quick as the direct MPC approaches because of this feature (e.g., FCS-MPC). For instance, the direct MPC techniques should have an action time of less than a millisecond, whereas the suggested MPC controller's action time can range from a few milliseconds to more.
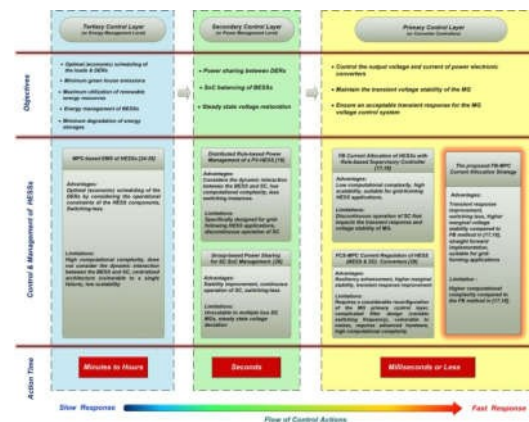
Fig(1):A comparison between different real time control and management strategies of HESSs with respect to the standard hierarchical control structure of DCMGs.

As a result, this method's optimization stage is simpler(i.e., more suitable for real-time applications) Additionally, neither the power electronic converters nor the dynamics of the MG circuit model are required by its prediction model. Additionally, it does not need details about other DERs, such as their output currents or voltages. Just the filter model, nominal current, and SC charge capacity are needed instead. Because of this, it has a much simpler prediction model. Its decentralised architecture also makes its simple to modify for the multi-generation/multi-bus DC MGs. It should be mentioned that the suggested FB-MPC method seeks to enhance the primary control layer performance of the MG. This work concentrates on the short-term operation of the system (i.e., in the range of a few seconds) to explore the transient response and voltage stability of the system under rapid load changes because the fundamental control layer of MG has very quick dynamic reactions. Therefore, the SoC management of BESS which often calls for long-term (or mid-term) EMS and power sharing methods and necessitates the right responses from the secondary and tertiary control layers of the MG—is not covered in this work. In terms of the control hierarchy of DC MGs, Fig. 1 contrasts the extent and contribution of this research with that of the reviewed literature. The remainder of this essay is structured as follows: In order to perform a small-signal stability study, Section II builds the dynamical model of the DCMG and outlines the suggested system design. The performance of the MG voltage control system can be negatively impacted by standard FB techniques, which is why using the suggested FB-MPC method may be beneficial. The suggested MPC-based SC SoC restoration technique is then covered in part III. In part IV, computer simulation is used to confirm the effectiveness of the suggested FB-MPC technique. The next directions for research are covered in Section V, and the work is concluded in Section VI.
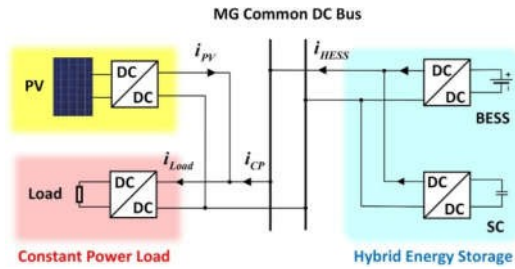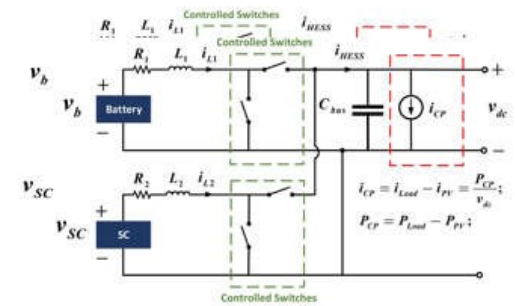
Fig(2):Theschematicmodelofthecasestudysystem.

Fig (3): The circuit model of the case study DC MG

system.II.SYSTEMANALYSIS:

The effect of an FB power/current allocation system on thedynamic stability of MG is examined in this section. Figure 2depicts an islanded DC MG with a PV power production system,aHESSmodule,

andaCPL;theHESS,load,andPVcurrentsarerepresented, respectively, byi_{HESS},i_{Load}, and i_{PV} . The differencebetween the load and PV currents is also represented by i_{CP} (i.e.,i_{CP},i_{Load},i_{PV}).TheconventionalsinglebusislandedDCMGsuggested in [17], [18], on which the case study system in thiswork is based, and in which the HESS regulates the common DCbusvoltage.Ascanbeseen,aBESSandSCarecontainedwithinthe HESS module and are both connected in parallel to the MGDC bus by means of bidirectional boost converters. The CPL isregarded as a DC load that is coupled to the MG DC bus via apower electronic converter (also known as a load converter) andrequires a constant amount of power under variable MG voltage.Here, it is assumed that the PV is operating as a Constant PowerSource(CPS)inMaximumPowerPointTracking(MPPT)mode.Additionally, the HESS functions as a grid-forming device tocontrol the MG DC bus voltage. The equivalent circuit model oftheislandedDCMGisshowninFig.3,where$v_b$andv_{SC}representthetterminalvoltagesoftheBESSandSC,respectively.Theoutputcurrent softheBESSandSCarei_{L1}andi_{L2},respectively, while the DC bus voltage is vdc. PCP is also thedifference between the power that the CPL (also known as P_{Load})demands and the power that the CPS generates (i.e., P_{PV}). As aresult, the grid-forming HESS module is charged by a CPS whenthe PV power generation exceeds the power required by the load(i.e., $P_{CP}<0$). On the other side, the HESS is loaded by a CPL iftheloadconverter'srequiredpowerisgreaterthanthePVgeneration power (i.e., $P_{CP} > 0$). It is important to note that CPLsnegative incremental resistance may reduce the dynamic stabilityofDCMGs[32],[33].Inordertoensuretheirdependablefunctioning,DCMGsthatcontainbigCPLsneedacontrolsystem withahighmarginalstability.

The traditional FB power allocation technique in a grid-formingHESS unit is shown in Fig. 4. In this configuration, the HESSmodule's reference current, or i_{ref}, is computed by a Proportional-Integral (PI) controller as part of the voltage regulator, whichcontrols the DC bus voltage. The HESS power allocation modulethen applies a high-pass filter to the HESS reference current (i.e.,i_{ref}) to extract its high frequency components. The HESS currentallocation system then performs two modes of operation dubbed"BESS-SC"and"BESS-only"inordertoguaranteethesecureand

dependableoperationofthesystem.Thesystemallocatesthehighfrequency components of the HESS reference current (i.e., i_{HPF})totheSCduring the"BESS-SC"operating mode(i.e.,S=1) (i.e.,i_{SC}=i_{HPF})(Forexample,i_b,i_{ref},i_{HPF}).Ontheotherside,thesupervisorycontrollermaydeactivatethefilter(orSC)andswitchto the "BESS-only" operating mode to avoid SC SoC violation(i.e., S =0). In this instance, the system assigns the BESS all ofthe reference current (i.e., i_b, i_{ref} , i_{SC}). Therefore, when the powerallocation filter is turned off (i.e., in "BESS-only" mode), theHESS functions like a single BESS. Fig. 5 depicts the condensedlogicoftherule-basedsupervisorycontrollerforSCSoCmanagement.Inordertoregulate theoutputcurrentsoftheBESSand SC converters to their reference values, i.e., $d_1$and d_2, thecurrent controllers determine the duty of cycle of each workingmode. The closed-loop system's state space dynamical modelutilising the dynamical model to compares the marginal stabilityoftheDCMGintotwodifferentoperatingmodes,namely"BESS-SC" and "BESS-ONLY", by analysing the small - signalstability of the system. It will also go over how the filters timeconstant(orbandwidth) affectstheclosed-loopsystem stability.
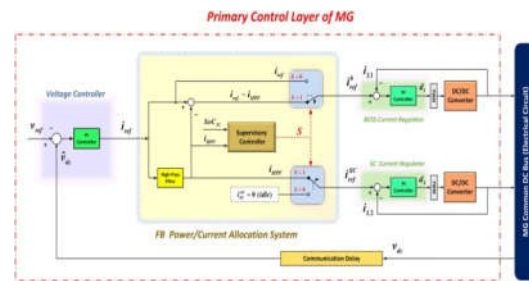
Fig(4):Thegrid-formingHESSstructurewiththetraditionalFBpower/currentallocation approach from[17],[18].

III. THEPROPOSEDFB-MPC METHOD:

TheproposedFB-MPCapproachisdisplayedinFig.6.Thevoltage controller at the MG's primary control layer computes areferencecurrentinthisway,whichissimilartotheFBapproach,tomanagethecommonDCbusvoltage.TheFB-MPCpower/currentallocationmechanismreceivesthisreferencecurrent after that. To ensure the continuous operation of the SCand filter, the suggested technique substitutes an MPC module(see Fig. 4) for the rule-based supervisory controller employed inthe traditional FB approach (see Fig. 3). In this method, the MPCmodule controls the SoC of the SC to a reference value whiletaking the SoC limitations of the SC into account. In order toaccomplishthis,theMPCcontrollerusesthediscretizeddynamical modelofthe systemtoforecastthe SoCofSC'sfutureerror fromitsreferencevalueoveramovinghorizon,alsoknownasthepredictionhorizon.Then,itcalculatesaseriesofcompensationcurrents(i_{com})withinamovinghorizon(i.e.,controlhorizon)andappliesthe firstoneto reducetheerror.Asaresult, the MPC compensator transmits a compensation term tothe HPF depending on the SoC fluctuation of SC and the HESSreferencecurrent(i.e.,i_{ref}).Thecompensatingtermisaddedtotherereference current of the SC after leaving the HPF and subtractedfrom the reference current of the BESS after leaving the HPF. Asa result, the MPC compensator offers additional BESS and SCcoordination so that the BESS gradually charges or releases theSC. As a result, the suggested FB-MPC can regulate the SoCvariationwithinaspecifiedrange,ensuringthecontinuedoperation of thefilterandSC.
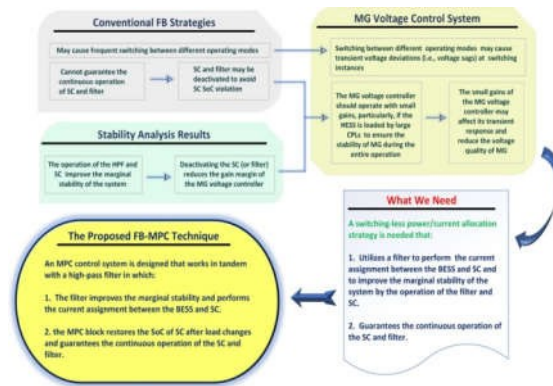
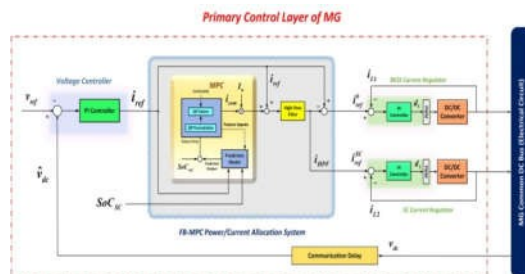**Fig(5):JustificationoftheproposedFB-MPCapproach**

Fig (6): The structure of a grid-forming HESS unit with theproposedFB-MPC power/current allocationsystem

As can be seen in Fig. 6, the MPC compensator receives the SoC of SC (i.e., SoC_{SC}) and the HESS reference current (i.e., i_{ref}) fromthe voltage controller in order to regulate the SC SoC variationwithin a predetermined range. In order to achieve this, the MPCcontroller uses a dynamic model of the FB current allocationsystemaswellasdynamicrelationshipbetweentheSC'scurrentand the SoC value during the prediction stage. In this case, theMPCcontrollerusesthedynamicmodeloftheFBcurrentallocation system to determine how much of the HESS referencecurrentwillbeassignedtothe SC,and thenforecaststhe SCSoCfluctuation throughout the course of its prediction interval (i.e.,thepredictionhorizon).TheMPCwillthenperformoptimization .By taking into account the SC SoC limitations specified in, thecontroller calculates a series of compensation terms, or icom, inorder to reduce the error between the SC's SoC and its referencevalue,orSoC_{ref}.Afterapplyingthefirstvalueinthesequence ,theMPCcontrolleradvancestothefollowingtimestep.Fig.7depictst he MPC compensator's flowchart. The HPF is then sent thecompensationterm.
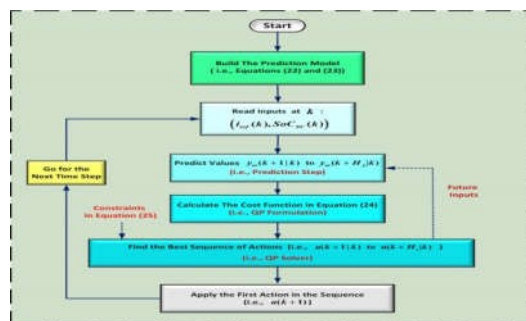

Fig (7): The flowchart of the proposed MPC strategy for SCSoC recovery

The continuous operation of the SC and filter cannot be ensuredbythetypicalFBpower/currentallocationtechnique.Asares ult,the HESS can alternate between the "BESS-only" and "BESS-SC"modesofoperation.TheMGvoltagecontrolsystemthenhas

much highermarginalstabilityinthe"BESS-SC"operatingmodecomparedtothe"BESS-only"operation,accordingtotheproposed small-signal stability analysis in II.B. As a result, anMPC controller is used to keep the SC's SoC variation within aset range, ensuring the continued operation of the SC and filter.TheHESSwillthereforealwaysbeinthe"BESS-SC"operationalmode. In order to accomplish this, the MPC controller computesa compensation term (i_{com}) and sends it to the HPF (see Fig. 6).As a result, the MPC controller adds the d_{com} to the SC referencecurrent and subtracts that value from the SC reference current tooffer extra coordination between the SC and BESS. Practicallyspeaking,theMPCactiontime(orMPCsamplingtime)iss ubstantially longer than the MG voltage controller since thedynamics of the SC SoC change are significantly slower thanthose of the DC bus voltage.Inthe MPCcost function, thevariationoftheMPCcompensationcurrent(i.e.,themovedvariabl e)isalsoconstrained.Thecompensationterm(i.e.,d_{com})isconsequentl y viewed from the perspective of the MG voltagecontroller as a minor disturbance with very slow fluctuations. Asa result, dcom does not alter the dynamic model of the MGvoltagecontrolsystem(suchas theclosed-loop polesof thelinearized model). Practically speaking, the MPC action time (orMPC sampling time) is substantially longer than the MG voltagecontrollersincethedynamicsoftheSCSoCchangearesignific antlyslowerthan thoseoftheDCbus voltage.

IV. SIMULATION RESULTS:

The dynamical behaviour of Case 1 (FB) and Case 2 (FB-MPC)systemsisevaluatedinthreeseparaterapidload(orP_{CP})variatio nsituations in order to assess the effectiveness of the FB-MPCmethodandcompareitwithtraditionalFB powerallocationstrategies. In the first scenario, the P_{CP} is abruptly increased from10to15Wattimet=10s,andthenabruptlydecreasedfrom15to 10 kW at time t = 25 s. The DC MG undergoes a quick andperiodicpulsed-shapechangeinP_{CP}inthesecondscenario.Inthefinal scenario, P_{CP} rapidly rises from 10kW to 19kW at t = 70sbefore dropping back to 10kW at t = 90s. The P_{CP} profile in thesethree load conditions is shown in Fig. 8. It ought to be It shouldbe emphasised that in reality, the first and third load changescenarioscouldoccurwhenaloadorsourceconverterisaddedo rremoved,whilethesecondloadchangescenarioisbroughtonbytheP PLs(suchaselectricpropulsionorlaserweapons)insidetheDCMG.

During thediscussedloadchangesituations,theoutputpowerofthe BESS and SC in Case 1 (i.e., FB) and Case 2 (i.e., FB-MPC)systemsisshowninFig.9.P_{SC}>0indicatesthattheSC isdischarging, while P_{SC}< 0 indicates that the SC is charging. Inboth the FB and FB-MPC approaches, the output power of theBESS is smoothed, and the high frequency changes of the P_{CP} areassignedtotheSC,asshowninFig.9(a)and(b).Additionally,inbot h scenarios, the HESS output power (i.e., P_{HESS} = P_b + P_{SC}) isequal to the P_{CP} (i.e., P_{HESS}=P_{CP}), indicating that power generationandloadareinbalance.DuetotheinfluenceoftheMPCcom pensator, the BESS and SC have slightly different outputpowerprofilesintheFB-MPCmethodcomparedtotheFBapproach.

As can be observed in Fig. 11(a), the MPC compensator addsanother level of coordination between the BESS and SC in theFB-MPCapproachbyallowingtheBESStoprogressivelychargeand discharge the SC while controlling its SoC variation within apredetermined range.Alargequantityofpoweris suppliedtotheSCin thethirdloadchangescenario(seeFigs.8and9)asaresultof the severe P_{CP}variations. As a result, according to the FBapproach,theSoCofSCachievesitslowestpermittedvalueatt = 73.1s (see Fig. 11(a)). In order to operate the BESS solely, therule-basedsupervisorycontrollerdeactivatestheSCanddistributes P_{HESS}

power to the BESS. At t = 90 s, the load powerabruptlydrops,causingtheHPFoutputtoturnnegative($i_{HPF}<0$).

Asaresult,therule-basedsupervisorycontrolleractivatestheSCandthe HESSreturns to working inthe"BESS-SC"mode.

The SoC of SC, on the other hand, roughly reaches its minimumvalue at t = 74.3s in Case 2 (i.e., FB-MPC), as a result of theabrupt change in load at t = 70s. The MPC parts in Case 1 (FB)and Case 2 (FB-MPC) systems are currently available. As can beobserved, the HPF allocates the SC the reference current's highfrequencycomponents(i.e.,abruptfluctuations)inordertosmooth out the BESS reference current. Additionally, it can beseenthat theSCinbothscenariosentirely absorbsthe highfrequency pulsed-shape load changes (i.e., Case 1 and Case 2).As previously mentioned, the SC (or filter) is disengaged at t =73sinthethird loadscenario.

The suggested FB-MPC technique (Case 2) and the standard FB(Case 1) are compared in Fig. 12, where Fig. 12(b) shows theoutput currents of the HESS components in the Case 1 (FB) andCase2(FB-MPC)systemsandFig.12(a)displaysHESSreference currents determined using MG voltage controllers. Ascan be observed, the HPF allocates the SC the reference current'shigh frequency components (i.e., abrupt fluctuations) in order tosmooth out the BESS reference current. Additionally, it can beseenthat theSCinbothscenariosentirely absorbsthe highfrequencypulsed-shapeloadchanges (i.e., Case1andCase2).

As previously established, in the third load scenario, the SC inorder to prevent a SC SoC violation, is turned off at t = 73.1s inCase1andtheHESSswitchestothe"BESS-only"operation.TheSC current is quickly switched to zero as a result, which can leadto a significant transient voltage sag. However, by including acompensating current, the suggested FB-MPC approach ensurestheuninterruptedoperationofSCduringthefullsystemoperat ionadding that amount to the SC and deducting it from the BESSreference current.

AsseeninFig. 13,whentheSoC ofSChitsitsminimalvalueatt = 74.3s, the d_{com} moves relatively quickly. The MPC forecaststhat its output constraint (i.e., the SC SoC allowed range) will bebroken att =73.1s.

TheBESSandSCterminalvoltagesduringthesimulationinterval are shown in Fig. 14. As can be observed, the terminalvoltage of the BESS (i.e., v_b) stays largely consistent during thesimulationsessiondespitetheBESShavingasubstantiallylongerc harge time (i.e., 2 hours). It is also important to note that thesuggestedFB-MPCstrategyresultsinadifferentterminalvoltageof the SC in Case 2 compared to Case 1 due to a distinct SoCvariation caused by the FB method (i.e., v_{SC}). As a result, duringsystem operation, the reference currents of the HESSs in Cases 1and 2 estimated by the MG voltage controller have somewhatdistinct profiles.
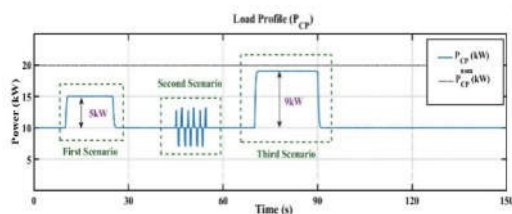
Fig(8).Theloadchange scenarios in the test systems

The dynamical behaviour of Case 1 (FB) and Case 2 (FB-MPC)systemsisevaluatedinthreeseparaterapidload(orP_CP)variatio nsituations in order to assess the effectiveness of the FB-MPCmethodandcompareitwithtraditionalFB powerallocationstrategies. In the first scenario, the P_{CP} is abruptly increased from10to15kWattimet=10s,andthenabruptlydecreasedfrom15to1 0kWattimet=25s.TheDCMGundergoesaquickand

periodic pulsed-shape change in PCP in the second scenario. Inthe final scenario, PCP rapidly rises from 10kW to 19kW at t =70s before dropping back to 10kW at t = 90s. The P_{CP} profile inthese three load conditions is shown in Fig. 8. It ought to be Itshould beemphasised that inreality, the first andthird loadchange scenarios could occur when a load or source converter isaddedor removed,while the second load change scenario isbrought on by the PPLs (such as electric propulsion or laserweapons) inside theDCMG.

During thediscussedloadchange situations,the outputpowerofthe BESS and SC in Case 1 (i.e., FB) and Case 2 (i.e., FB-MPC)systems isshowninFig.9.P_SC>0indicatesthattheSC isdischarging, while $P_{SC} < 0$ indicates that the SC is charging. Inboth the FB and FB-MPC approaches, the output power of theBESS is smoothed, and the high frequency changes of the P_{CP} areassignedtotheSC,asshowninFig.9(a)and(b).Additionally,inbot h scenarios, the HESS output power (i.e., $P_{HESS} = P_b + P_{SC}$) isequaltothePCP(i.e.,$P_{HESS}=P_{CP}$),indicatingthatpowergeneration and load are in balance. Due to the influence of theMPCcompensator,theBESS and SC haveslightlydifferentoutputpowerprofilesintheFB-MPCmethodcomparedtotheFBapproach.

(a)

(b)
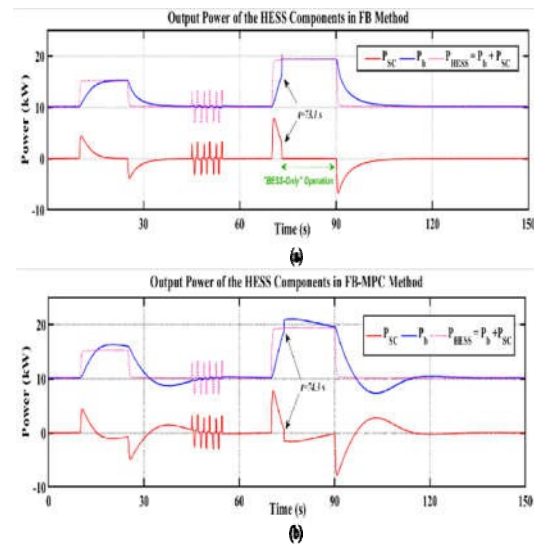
Fig (9).The output power of the HESS components in the test(a)Case1(i.e., conventional FB), (b) Case 2 (i.e., the proposedFB-MPC).
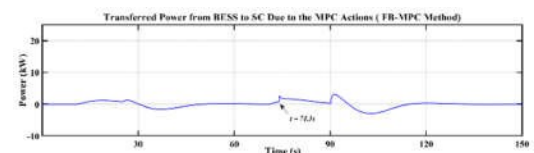

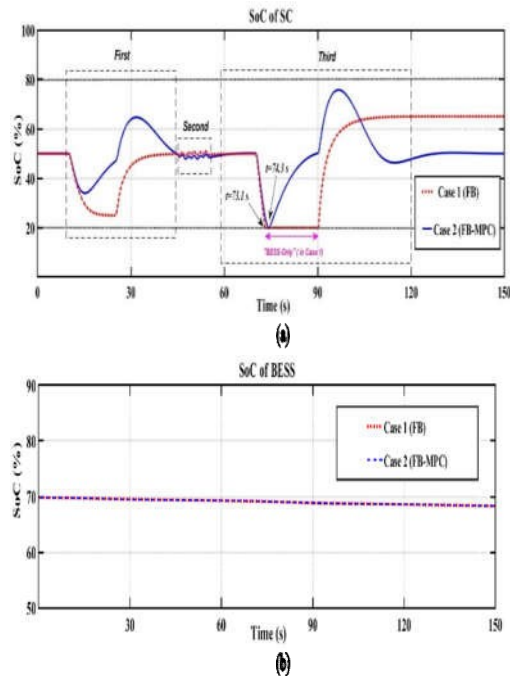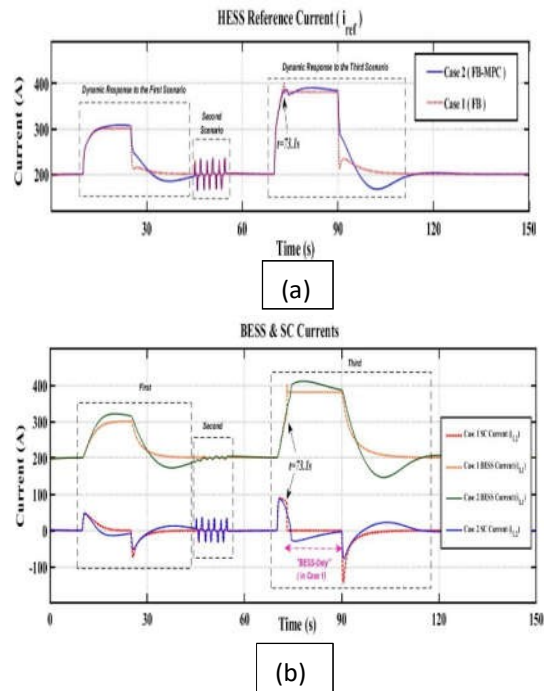Fig (10). Transferred power from BESS to SC because of theMPCactionsinthe FB-MPCmethod.

Fig (11). The SC and BESS SoC variation (a) SoC of SC, (b)SoC ofBESS

As can be observed in Fig. 11(a), the MPC compensator addsanother level of coordination between the BESS and SC in theFB-MPCapproachbyallowingtheBESStoprogressivelychargeand discharge the SC while controlling its SoC variation within apredeterminedrange.Alargequantityofpowerissuppliedto theSC in the third load change scenario (see Figs. 13 and 14) as aresult of the severe PCP variations. As a result, according to theFB approach, the SoC of SC achieves its lowest permitted valueat t = 73.1s (see Fig. 11(a)). In order to operate the BESS solely,therule-basedsupervisorycontrollerdeactivatestheSCanddistributesPHES SpowertotheBESS.Att=90s,theloadpowerabruptly drops, causing the HPF output to turn negative ($i_{HPF}<0$).Asaresult,therule-basedsupervisorycontrolleractivatestheSCandthe HESSreturns to working in the"BESS-SC"mode.

The SoC of SC, on the other hand, roughly reaches its minimumvalue at t = 74.3s in Case 2 (i.e., FB-MPC), as a result of theabrupt change in load at t = 70s. The MPC parts in Case 1 (FB)and Case 2 (FB-MPC) systems are currently available. As can beobserved, the HPF allocates the SC the reference current's highfrequencycomponents(i.e.,abruptfluctuations)inordertosmoot h out the BESS reference current. Additionally, it can beseenthat theSCinbothscenariosentirely absorbsthe highfrequency pulsed-shape load changes (i.e., Case 1 and Case 2).As previously mentioned, the SC (or filter) is disengaged at t =73sinthethird loadscenario.

(a)

(b)

Fig(12).Theperformanceofthecurrentallocationsystemsinthec asestudyMGs(i.e.,Case1andCase2).(a)HESSreference current(b)The SCandBESScurrents.

The suggested FB-MPC technique (Case 2) and the standard FB(Case 1) are compared in Fig. 12, where Fig. 12(b) shows theoutput currents of the HESS components in the Case 1 (FB) andCase2(FB-MPC)systemsandFig.12(a)displaysHESSreference currents determined using MG voltage controllers. Ascan be observed, the HPF allocates the SC the reference current'shigh frequency components (i.e., abrupt fluctuations) in order tosmooth out the BESS reference current. Additionally, it can beseenthattheSC inbothscenarios entirelyabsorbs the highfrequencypulsed-shapeloadchanges(i.e., Case1andCase2).

As previously established, in the third load scenario, the SC inorder to prevent a SC SoC violation, is turned off at t = 73.1s inCase1andtheHESSswitchestothe"BESS-only"operation.TheSC current is quicklyswitched to zero, whichcan leadto asignificanttransientvoltagesag.However,byincludingacompensat ing current, the suggested FB-MPC approach ensurestheuninterruptedoperationofSCduringthefullsystemoperat ionadding that amount to the SC and deducting it from the BESSreference current.
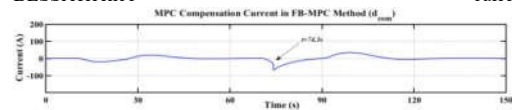

FIGURE 13.The MG DC bus voltage during the load changescenarios.

As seen in Fig. 13, when the SoC of SC hits its minimal value att = 74.3s, the d_{com}moves relatively quickly. The MPC forecaststhat its output constraint (i.e., the SC SoC allowed range) will bebroken att =73.1s.
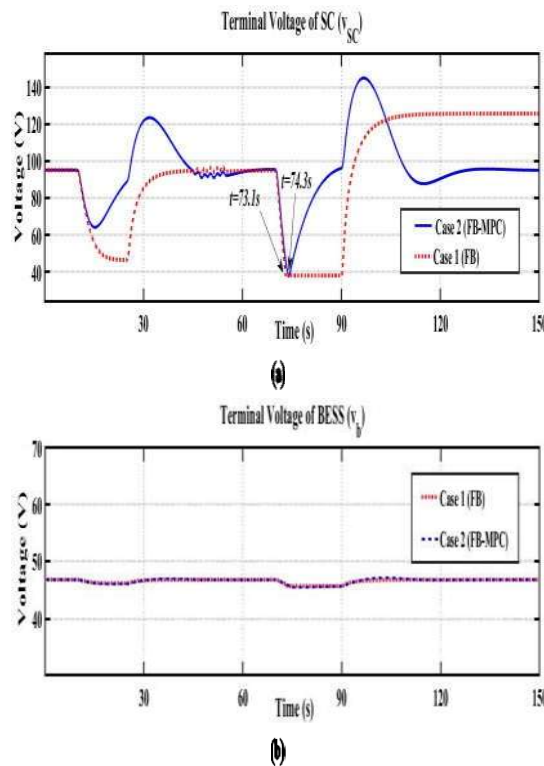
Fig (14). The output power of the HESS components in the test cases (a) Case1 (i.e., conventional FB), (b) Case 2 (i.e., the proposed FB-MPC).

The BESS and SC terminal voltages during the simulation interval are shown in Fig. 14. As can be observed, the terminal voltage of the BESS (i.e., v_b) stays largely consistent during the simulation session despite the BESS having a substantially longer charge time (i.e., 2 hours). It is also important to note that the suggested FB-MPC strategy results in a different terminal voltage of the SC in Case 2 compared to Case 1 due to a distinct SoC variation caused by the FB method (i.e., v_{SC}). As a result, during system operation, the reference currents of the HESSs in Cases 1 and 2 estimated by the MG voltage controller have somewhat distinct profiles.
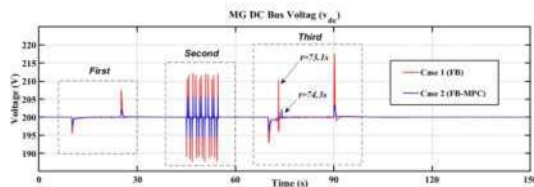

Fig(15). The MG DC bus voltage during the load change scenarios.

CONCLUSION

FB techniques are widely used in HESS applications to achieve the power/current allocation between the BESS and SC. An LTI filter is frequently used to separate the high and low-frequency components of the HESS reference power/current, with the high-frequency components then being assigned to SC. This paper initially presents a small-signal stability analysis to ascertain the impacts of the HESS current assignment filter on the dynamic stability of a single bus DC MG in which a grid-forming HESS supplies a CPL. The stability analysis demonstrates that the present assignment filter improves the marginal stability of the

MG. The MG PI voltage controller can work at higher gain settings and withstand longer communication delays than ks to the continuous operation of the SC and filter. The SC and filter cannot, however, work continuously under rapid load fluctuations when employing the typical FB techniques. In order to develop an MPC-based SC SoC restoration solution that addresses this problem, the current allocation between the BESS and SC is carried out in this research together with an LTI filter. In this system, the SC and filter are guaranteed to operate continuously since the MPC controller maintains the SoC of the SC within a set range. As a result, the suggested method indirectly enhances the system's transient response and voltage quality by allowing the MG voltage controller to operate at greater gain levels. After that, a case study DC MG simulation in MATLAB/Simulink is used to confirm the effectiveness of the suggested FB-MPC approach.

REFERENCES

[1] M. Fotuhi Firuzabad, R. Iravani, F. Aminifar, N. Hatziargyriou, an M. Lehtonen, ''Guest editorial special section on microgrids,'' *IEEE Trans. Smart Grid*, vol.3, no.4, pp.1857–1859, Dec.2012.

[2] M. Ahmed, L. Meegahapola, A. Vahidnia, and M. Datta, ''Stability and control aspects of microgrid architectures—A comprehensive review,'' *IEEE Access*, vol.8, pp. 144730–144766, 2020.

[3] L. Meng, Q. Shafiee, G.F. Trecate, H. Karimi, D. Fulwani, X. Lu, and J. M. Guerrero, ''Review on control of DC microgrids and multiple microgrid clusters,'' *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 5, no.3, pp. 928–948, Sep.2017.

[4] M.K. Al-Nussairi, R. Bayindir, S. Padmanaban, L. Mihet-Popa, and P. Siano, ''Constant power loads (CPL) with microgrids: Problem definition, stability analysis and compensation techniques,'' *Energies*, vol. 10, no. 10, p.1656, Oct.2017.

[5] O. Lorzadeh, I. Lorzadeh, M.N. Soltani, and A. Hajizadeh, ''Source-side virtual RC damper-based stabilization technique for cascaded systems in DC microgrids,'' *IEEE Trans. Energy Convers.*, vol.36, no.3, pp.1883–1895, Sep.2021.

[6] M. Hassan, M. Worku, A. Eladl, and M. Abido, ''Dynamic stability performance of autonomous microgrid involving high penetration level of constant power loads,'' *Mathematics*, vol.9, no.9, p. 922, Apr.2021.

[7] Q. Xu, N. Vafamand, L. Chen, T. Dragicevic, L. Xie, and F. Blaabjerg, ''Review on advanced control technologies for bidirectional DC/DC converters in DC microgrids,'' *IEEE J. Emerg. Sel. Topics Power Electron.*, vol.9, no.2, pp.1205–1221, Apr.2021.

[8] Y. Wang, L. Wang, M. Li, and Z. Chen, ''A review of key issues for control and management in battery and ultra-capacitor hybrid energy storage systems,'' *eTransportation*, vol.4, May 2020, Art. no.100064.

[9] A.A.K. Arani, G.B. Gharehpetian, and M. Abedi, ''Review on energy storage systems control methods in microgrids,'' *Int. J. Electr. Power Energy Syst.*, vol. 107, pp.745–757, May 2019.

[10] M.E. Şahin and F. Blaabjerg, ''A hybrid PV-battery/supercapacitor system and a basic active power control proposal in MATLAB/Simulink,'' *Electronics*, vol.9, no. 1, p. 129, Jan.2020.

[11] S. Hajiaghasi, A. Salemnia, and M. Hamzeh, ''Hybrid energy storage system for microgrids applications: A review,'' *J. Energy Storage*, vol. 21, pp. 543–570, Feb.2019.

[12] N.R. Tummuru, U. Manandhar, A. Ukil, H.B. Gooi, S.K. Kollimalla, and S. Naidu, ''Control strategy for AC-DC microgrid with hybrid energy storage under different

operatingmodes,''*Int.J.Electr.PowerEnergySyst.*,vol.104, pp.807–816,Jan.2019.

[13] V.T.NguyenandJ.W.Shim,''Virtualcapacityofhybridenerg y storage systems using adaptive state of chargerange control for smoothing renewable intermittency,''*IEEE Access*,vol.8,pp.126951–126964,2020.

[14] W. Jing, C. H. Lai, W. S. H. Wong, and M. L. D. Wong,''Dynamicpowerallocationofbattery-supercapacitorhybridenergystorageforstandalonePVmicr ogridapplications,'' Sustain.*Energy Technol.Assessments*,vol.22, pp. 55–64, Aug. 2017.

[15] X. Lu, Y. Chen, M. Fu, and H. Wang, ''Multi-objectiveoptimization-basedreal-timecontrolstrategyforbattery/ultracapacitorhybridenergy managementsystems,''*IEEEAccess*,vol.7,pp.11640–11650,2019.

[16] X.Chang,Y.Li,X.Li,andX.Chen, ''Anactivedampingmethod based on a supercapacitor energy storage systemtoovercomethedestabilizingeffectofinstantaneousc onstant power loads in DC microgrids,'' *IEEE Trans.EnergyConvers.*,vol.32,no.1,pp. 36–47,Mar.2017.

[17] S.KotraandM.K.Mishra,''DesignandstabilityanalysisofD Cmicrogrid with hybrid energy storage system,'' *IEEETrans. Sustain. Energy*, vol.10, no. 3, pp. 1603–1612,Jul.2019.

[18] P.SinghandJ.S.Lather,''Powermanagementandcontrolof a grid- independent DC microgrid with hybrid energystorage system,'' *Sustain. Energy Technol. Assessments*,vol. 43, Feb. 2021, Art. no100924.

[19] S. A. G. K. Abadi and A. Bidram, ''A distributed rule-basedpowermanagementstrategyinaphotovoltaic/hybrid energy storage based onan activecompensationfiltering technique,'' *IET Renew. PowerGener.*,vol.15,no.15,pp.3688–3703,Nov.2021.

[20] Q.Xu, X.Hu, P. Wang, J. Xiao, P.Tu, C. Wen, and M.Y.Lee,decentralizeddynamicpowersharingstrategyforh ybridenergystoragesysteminautonomousDCmicrogrid,''*I EEETrans.Ind.Electron.*,vol.64,no.7,pp.5930–5941,Jul.2017.

[21] U.B.Tayab,M.A.Roslan,L.J.Hwai,andM.Kashif,''Arevie wofdroopcontroltechniquesformicrogrid,''*Renew. Sustain. Energy Rev.*, vol. 76, pp. 717–727, Sep.2017.

[22] J. Hu, Y. Shan, J. M. Guerrero, A. Ioinovici, K. W. Chan,andJ.Rodriguez''Modelpredictivecontrolofmicrogri ds—Anoverview,''*Renew.Sust.Energ.Rev.*,vol.136,Feb.2021, Art. no.110422.

[23] P.Karamanakos,E.Liegmann,T.Geyer,andR.Kennel,''Mo delpredictivecontrolofpowerelectronicsystems:Methods,r esults,andchallenges,''*IEEEOpenJ.Ind.Appl.*,vol. 1,pp.95–114,2020.

[24] U. R. Nair and R. Costa-Castello, ''A model predictivecontrol-basedenergymanagementschemeforhybridstorage system in islanded microgrids,'' *IEEE Access*,vol. 8,pp.97809–97822,2020.

[25] X. Zhang, B. Wang, D. Gamage, and A. Ukil, ''Modelpredictive and iterative learningcontrol-based hybridcontrolmethodforhybridenergystoragesystem,''*IE EETrans. Sustain.Energy*, vol. 12, no.4,pp. 2146–2158,Oct. 2021.

[26] H.Chen,R.Xiong,C.Lin,andW.Shen,''Modelpredictive control based real-time energy managementfor hybrid energy storage system,'' *CSEE J.PowerEnergySyst.*,vol.7,no.4,pp.862–874, Jul.2021.

[27] Z.Jia,J.Jiang,H.Lin,andL.Cheng,''Areal-timeMPC-basedenergymanagementofhybridenergystoragesystem in urban rail vehicles,'' *Energy Proc.*, vol. 152,pp.526–531,Oct.2018.

[28] F.Garcia-Torres,L.Valverde,andC.Bordons,''Optimalload sharing of hydrogen-based microgrids with hybridstorage using model-predictive control,'' *IEEE Trans.Ind.Electron.*,vol.63,no.8,pp.4919–4928,Aug.2016.

[29] F.Ni,Z.Zheng,Q.Xie,X.Xiao,Y.Zong,andC.Huang,''Enh ancing resilience of DC microgrids withmodelpredictivecontrol-basedhybridenergystoragesystem,''*Int. J. Electr. Power Energy Syst.*, vol.128, Jun. 2021,Art.no.106738.

[30] A. Ebrahimian, S. Vahid, N. Weise, and A. El-Refaie,''Two level AC- DC-AC converter design with a newapproachtoimplementfinitecontrolsetmodelpredictiv e control,'' in *Proc. 22nd IEEE Int. Conf. Ind.Technol.(ICIT)*, Mar.2021,pp.514–520.

[31] M.Aguirre,S.Kouro,C.A.Rojas,J.Rodriguez,andJ.I.Leon ,''Switching frequency regulation for FCS-MPC basedonaperiodcontrolapproach,''*IEEETrans.Ind.Electr on.*,vol.65,no.7,pp. 5764–5773, Jul.2018.

[32] Z.Karami,Q.Shafiee,S.Sahoo,M.Yaribeygi,H.Bevrani,and T.Dragicevic,''HybridmodelpredictivecontrolofDC–DC boost converters with constant power load,'' *IEEETrans.Energy Convers.*, vol. 36, no. 2, pp. 1347–1356,Jun.2021.

[33] S. Singh, A. R. Gautam, and D. Fulwani, ''Constantpower loads and their effects in DC distributed powersystems: A review,'' *Renew. Sustain. Energy Rev.*, vol.72,pp.407–421, May2017.

[34] X. Lu, K. Sun, J. M. Guerrero, J. C. Vasquez, L. Huang,and J. Wang, ''Stability enhancement based on virtualimpedanceforDCmicrogridswithconstantpowerlo ads,'' *IEEE Trans.Smart Grid*, vol.6, no.6, pp.2770–2783,Nov.2015.

[35] H.R.Baghaee,M.Mirsalim,G.B.Gharehpetian,and H.A.Talebi,''Ageneralizeddescriptor-systemrobust$H$ control of autonomous microgrids to improve small andlarge signal stability considering communication delaysand load nonlinearities,'' *Int. J. Electr. Power EnergySyst.*,vol.92,pp.63–82,Nov.2017.

[36] K. Gu, J. Chen, and V. Kharitonov, *Stability of Time-DelaySystems*.Boston, MA,USA:Springer, 2003.

[37] G. Van den Broeck, J. Stuyts, and J. Driesen, ''A criticalreview of powerqualitystandardsanddefinitionsappliedtoDCmicro grids,''*Appl.Energy*,vol.229, pp.281–288,Nov.2018.

[38] Y. Han, X. Ning, P. Yang, and L. Xu, ''Review of powersharing, voltage restoration and stabilization techniquesinhierarchicalcontrolledDCmicrogrids,''*IEE EAccess*,vol.7, pp. 149202–149223,2019.