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REAL-TIME MODEL PREDICTIVE CONTROL OF BATTERY ENERGY STORAGE ACTIVE AND REACTIVE POWER TO SUPPORT THE DISTRIBUTION NETWORK OPERATION

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Abstract

This paper proposes a model predictive control technique to optimally dispatch of battery energy storage systems (BESS) installed on the medium voltage distribution network to manage the violations in addition to enhancing the power quality and stability. A two-phase strategy is developed to manage the BESS inverter power on the four active/reactive power quadrants. A multiobjective function is formulated in order to optimize the system voltage, power factor and line losses. The uncertainties associated with demand and generation forecasting are considered in the proposed strategy by introducing a real-time operational phase. The network, BESS, and inverter technical constraints are considered, and the proposed strategy is validated by simulating different scenarios on an 11 kV, 53-node distribution network located in Northern Ireland.

1 Introduction

In the electrical system, the conventional generators and different types of distributed generation (DG) provide the network with active and reactive power. However, due to the reactive power effect of raising the system voltage, the majority of DGs are not allowed to inject reactive power and these DGs are operated on a leading power factor [1]. Yet, the generation from photovoltaics (PV) and wind power is increasing rapidly and distribution system operators (DSOs) are investigating feasible solutions to provide the network with the required reactive power without violating the network's operational limits. Reactive power compensators are being used to support any reactive power shortfall, however, most of these devices cannot provide dynamic response such as (static VAR compensators and Capacitor banks), and while the static synchronous compensator (STATCOM) can offer dynamic response, their cost is high and their applications are limited.

Another solution is being embraced by DSOs through managing the PV/Wind power electronic devices to provide the network with the reactive power (injection/absorption), such as the nodal controller project by Northern Ireland Electricity (NIE) Networks [1]. The aim of this nodal controller is to control the reactive power dispatch of different resources such as wind farms to deliver reactive power services in terms of voltage control, power factor (PF) and reactive power support. This controller dispatches reactive power according to set points received from the DSO. The nodal controller links with the wind farms' local voltage controllers in order to control the voltage using the direct voltage control with slope principle, additionally, if necessary, it can control the transformer on-load tap changer (OLTC) to meet the voltage requirement.

Other studies have addressed the reactive power management of DGs to improve network performance. In [2], an approach is proposed to regulate the bus voltages using the reactive power of the doubly fed induction generator-based wind generation in a microgrid using the voltage sensitivity analysis. In [3], another voltage regulation approach is introduced by managing the PV DG inverters reactive power as well as the transformer OLTC. Battery energy storage systems (BESS) can be effectively managed to provide the required active and reactive power support to the distribution network. In [4], an active/reactive power management approach is proposed for BESS installed in medium voltage (MV) distribution networks. The objectives are to provide the network with the active and reactive power required for voltage regulation using droop control, in addition to shaving the load profile peaks.

The BESS can be operated to provide different services associated with network operation. Unlike the DGs and reactive compensation devices, BESS equipped with an appropriate inverter can inject and absorb both active and reactive power in addition to providing dynamic services in fast response. Additionally, BESS can be used for load levelling. Notably, the deployment of BESS will accelerate the secure accommodation of more renewable energy resources on the grid and hasten the progress towards net-zero target.

This paper proposes a model predictive control (MPC) for the BESS to enhance the overall performance of the MV distribution network (DN). The main contributions are summarized as follows: 1) proposing a novel optimization strategy of two algorithms to optimally utilize the BESS inverter active/reactive power to solve any violation that may occur as well as enhancing the system's power quality, 2) the uncertainties associated with the demand and renewable generation forecasting in addition to unexpected events are considered by introducing a real-time operation phase, 3) a powerful optimization solver is tested and introduced to this type of problems, 4) finally, different cases were simulated on an actual distribution network located in Northern Ireland.

2 Proposed Model Predictive Control

The BESS inverter operates on the four P-Q quadrants, during the BESS discharging mode, the inverter operates in the quadrants where the active power is being injected from the BESS to the network. While, for the charging mode, it operates in the quadrants where the active power is being absorbed by the BESS. Additionally, the inverter can act as a capacitive load by injecting reactive power and can act as an inductive load by consuming reactive power. These features allow the inverter to operate in all PF modes (1 to -1).

The proposed MPC consists of two phases as shown in Fig. 1, the first phase determines the initial setpoints of the inverter active/reactive power at each time-point within the dispatch horizon in a look-ahead basis based on forecasted data of demand and DGs. The second phase uses these initial setpoints as starting values for its optimization process and determines the final optimal active/reactive setpoints in a real-time basis for each time-point to overcome the uncertainties associated with the forecasted data. The first phase considers 80-90% of the BESS capacity in its optimization process, while the second phase considers the full BESS capacity. This assumption is introduced to give the real-time phase a wider search space in settling the optimal active power values and to prevent the algorithm from exceeding the total BESS capacity as this phase is executed for each time-point individually.

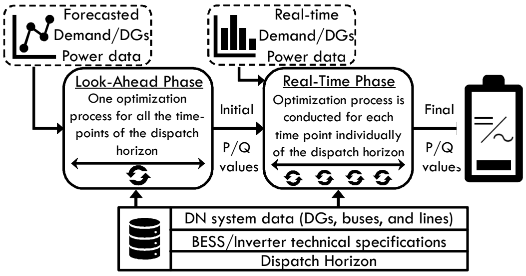

Fig. 1. Proposed model predictive control

Phase-I is introduced as a long/short-term planning in a look-ahead basis and to determine the initial points for Phase-II, which heavily reduces the processing time of Phase-II and improves the output results. Phase-I uses the full forecasted dispatch horizon in one optimization process and deals with the BESS capacity as a constraint which assures that the total active power dispatch will not exceed the BESS capacity. Phase-II is executed for each time-point individually and the active power dispatch at Phase-II is constrained using the active power values obtained from Phase-I in addition to 10-20% residual capacity to avoid exceeding the BESS capacity.

The proposed MPC aims to optimize the DN operation by regulating the voltage, power factor and line losses. The bus voltages are given a higher priority over the other objectives due to its impact on the network, if there are any voltage violations, the algorithm will focus on solving the voltage issue by determining the optimal active/reactive power values to be handled by the BESS inverter. For each time-point, the algorithm checks the network status and evaluates the multiobjective function (MOF) using power flow calculations. For multiple BESS, all the existing BESS will be considered by the model and the algorithm will find the best setpoints of each BESS to support the network in Phase-I. While, during the real-time phase (Phase-II), the model will adjust the power setpoints for each BESS to maintain the stability of the system.

3 MPC Mathematical Formulation

MOF is formulated for three objectives; voltage optimization, power factor maximization, and line losses minimization. The main objectives are to optimize the power factor at the substation node and minimize the system total real line losses. However, the voltage objective is added in case of violations in order to focus on solving the voltage issue if any violations occur. This MOF (*f_x*) is formulated using the weighted sum method expressed at time *t* as:

$$min \left(\begin{array}{c} k_1 \left(c_1 \frac{1}{PF_t} + c_2 PF_t \right) + k_2 V_t^{max} + k_3 \left({}^{1}\!/_{V_t^{min}} \right) \\ + k_4 \sum_{b=1}^{n-1} |I_{b,t}|^2 \, R_b \end{array} \right) \tag{1}$$

$$Where \quad c_1, c_2, k_1, k_2, k_3, and\ k_4 \ \in [1{,}0] \tag{2}$$

$$c_1 = 1, c_2 = 0 \rightarrow PF > 0 \tag{3}$$

$$c_1 = 0, c_2 = 1 \rightarrow PF < 0 \tag{4}$$

$$k_1 = 1 \ and \ \ k_2, k_3, k_4 = 0 \ \rightarrow |PF| < 0.9, \\ V_t^{min} > 0.95 \ \ and\ V_t^{max} < 1.05 \tag{5}$$

$$k_2 = 1 \ and \ \ k_1, k_3, k_4 = 0 \ \rightarrow V_t^{max} > 1.05 \tag{6}$$

$$k_3 = 1 \ and \ \ k_1, k_2, k_4 = 0 \ \rightarrow V_t^{min} < 0.95 \tag{7}$$

$$k_1, k_4 = 0.5 \ and\ k_2, k_3 = 0 \rightarrow V_t^{min} > 0.95, \\ V_t^{max} < 1.05 \ \ and \ \ |PF\,| > 0.9 \tag{8}$$

The *PF* is the power factor calculated at the substation node, V_t^{max} is the maximum bus voltage within the network, V_t^{min} is the minimum bus voltage in the DN, *n* is the number of buses, *b* is the branch number, while *t* is index of time. The proposed algorithm follows some rules in evaluating the objective function, in case of violations of bus voltages or *PF*, the MOF is converted into a single objective using the weighting coefficients $(k_1, k_2, k_3, and\ k_4)$. Otherwise, the algorithm will focus on optimizing the *PF* and line losses as a MOF, for this case, the MOF is converted into a mono-objective function by normalization/scaling using the consequent upper-bound approach [5].

The c_1 and c_2 are introduced to distinguish between *-ve* and *+ve* power factors, as if the *PF* is *-ve* (reverse power flow from the grid to the substation), the optimization will attempt minimizing the *PF* by pushing it towards -1, for the *+ve PF*, the optimization will maximize its value towards the value of 1 by minimizing its inverse. The *PF* at substation node can be mathematically calculated as:

$$PF_t = \frac{P_t^{ss}}{S_t^{ss}} \tag{9}$$

Where P_t^{ss} is the substation active power and S_t^{ss} is the substation apparent power and can be calculated as follows:

$$P_t^{ss} = \sum_{i=1}^{n} P_{i,t}^{demand} + \sum_{b=1}^{n-1} |I_{b,t}|^2 \, R_b \pm \sum_{m=1}^{e} P_{m,t}^{BESS} - \sum_{j=1}^{d} P_{j,t}^{DG} \tag{10}$$

Where *d* is the number of DGs, *e* is the number of BESS and $P_{m,t}^{BESS}$ is *-ve* for discharging and *+ve* for charging.

$$S_t^{ss} = \sqrt[2]{(P_t^{ss})^2 + (Q_t^{ss})^2} \tag{11}$$

$$Q_t^{ss} = \sum_{i=1}^{n} Q_{i,t}^{demand} + \sum_{b=1}^{n-1} I_{b,t}^2 \, X_b \pm \sum_{m=1}^{e} Q_{m,t}^{BESS} - \sum_{j=1}^{d} Q_{j,t}^{DG} \tag{12}$$

Q_t^{ss} is the substation reactive power, $Q_{m,t}^{BESS}$ is *-ve* for injection and *+ve* for absorption.

In case of voltage violation, the algorithm regulates the voltage by maximizing the V_t^{min} or minimizing the V_t^{max} while ensuring that the voltage profile is in the stable region in the normal operation. Optimizing the minimum and maximum voltage values will optimize and regulate the voltage at each bus. The algorithm performs power flow calculations using Newton Raphson method [6], in order to evaluate the Jacobian matrix and sensitivity matrices ${\partial v}/{\partial q}$ and ${\partial v}/{\partial p}$ to determine the necessary amount of *P* and *Q* to regulate the voltage at each bus. The optimization algorithm controls the voltage by determining the *P* and *Q* that should be handled by the inverter to regulate and optimize the bus voltages. The MOF is subjected to network constraints expressed as follows:

- Voltage Limits*:* The voltage magnitude at each bus should be within the allowable limits (0.95 p.u to 1.05 p.u).

$$0.95 \leq V_{i,t} \leq 1.05 \tag{13}$$

- Line flow Limits: The current flows in each branch should not surpass the ampacity of the branch.

$$I_{b,t} \leq I_b^{max} \tag{14}$$

- Inverter Rating: The power handled by the inverter at any time must not exceed the inverter rating.

$$S_t^{inv} \leq S_{max}^{inv} \tag{15}$$

$$S_{max}^{inv} = V_t^{inv} \times I_{max}^{inv} \tag{16}$$

$$S_t^{inv} = \sqrt[2]{(P_t^2)^{inv} + (Q_t^2)^{inv}} \tag{17}$$

- BESS State of Charge (*SoC*): At any time, the BESS SoC must not surpass the predefined values.

$$SoC_{min} \leq SoC_{BESS} \leq SoC_{max} \tag{18}$$

$$E_{us}^{BESS} = (SoC_{max} - SoC_{min}) \times E_a^{BESS} \tag{19}$$

  Where E_{us}^{BESS} is the usable BESS capacity and E_a^{BESS} is the actual BESS capacity in (kWh).

- BESS capacity: The total discharged or charged power for a total period of *T* time-points must not exceed the BESS available capacity.

$$\left(\sum_{t=1}^{T} P_t^{BESS}\right)\tau \leq E_{us}^{BESS} \tag{20}$$

  Where τ represents the interval time period such that $\tau = \frac{dm}{60}$ (dm is the data resolution in minutes $\tau = 0.5$ for 30-minute resolution, $\tau = \frac{1}{12}$ for 5-minute resolution, and $\tau = 1$ for 1-hour resolution). For Phase-I, the available BESS capacity (E_{us}^{I}) is constrained by a factor 90% as follows:

$$E_{us}^{I} = 0.9 \times E_{us}^{BESS} \tag{21}$$

  Typically, 80-90% is enough to increase the search space for Phase-II.

- Hourly Rate (*R_h*): The BESS power is limited by the hourly rate (Rate of charge and the Rate of discharge) which is either specified by the manufacturer or calculated using the minimum time of charging or discharging.

$$E_{us,h}^{BESS} = R_h \times E_{us}^{BESS} \tag{22}$$

  Where $E_{us,h}^{BESS}$ is the BESS maximum hourly capacity.

- BESS power rating: the output/input power of the BESS must not exceed its maximum rating at any time.

$$0 \leq P_t^{BESS} \leq P_{max}^{BESS} \quad \forall \quad t \in T \tag{23}$$

The proposed MOF is a constrained nonconvex problem that requires robust optimzer. Another important factor affects the selection of the proper solver, is the processing time. The time used by the optimizer to find the optimal solutions is crucial, especially for Phase-II as the inverter setpoints should be obtained in a very fast manner to be executed online. Different global and nonlinear optimization solvers were tested. NOMAD, and IPOPT have proven to converge and provide satisfactory results, however, their execution time was very long. Other solvers such as NLOPT, and FilterSD, were tested also but they failed to solve the MOF properly. All these solvers are well-known and have been used in many applications, however, for the proposed optimization problem, the European Nonlinear Programming Solver (WORHP) achieved the best results among these solvers in a very fast manner. The WORHP adopts sequential quadratic programming and interior point method to solve the large-scale sparse problems efficiently in a less computational manner [7].

The WORHP determines the decision variables *x* represented in the *P* and *Q* of the inverter at each time-point. For each iteration, a power flow calculation is solved using Newton Raphson and then the algorithm evaluates the objective function. Afterwards, the WORHP updates the iterations and the solution variables until the optimal solution is found. The flowchart of the proposed MPC is presented in Fig. 2.

The upper bounds (u_b) and lower bounds (l_b) for each solution variable at each time-point are given as:

$$u_{b,t}^{Q} = S_{max}^{inv} \; and \; l_{b,t}^{Q} = -S_{max}^{inv} \rightarrow reactive \; power \tag{24}$$

- Active power bounds for Phase-I:

$$u_{b,t}^{P} = P_{max}^{BESS} \quad and \quad l_{b,t}^{P} = 0 \rightarrow \quad charging \tag{25}$$

$$u_{b,t}^{P} = 0 \quad and \; l_{b,t}^{P} = -P_{max}^{BESS} \rightarrow \quad discharging \tag{26}$$

$$\sqrt[2]{(P_t^2)^I + (Q_t^2)^I} \leq S_{max}^{inv} \tag{27}$$

$$\left(\sum_{t=1}^{T} P_t^{I}\right)\tau \leq E_{us}^{I} \tag{28}$$

- Active power bounds for Phase-II:

$$\Delta_{re}^{BESS} = E_{us}^{I} - \left(\sum_{t=1}^{T} P_t^{I}\right)\tau \tag{29}$$

$$u_{b,t}^{P} = P_t^I + \frac{\Delta_{re}^{BESS}}{T} + \frac{0.1 \times E_{us}^{BESS}}{T}, \qquad l_{b,t}^{P} = 0 \rightarrow \; charging \tag{30}$$

$$u_{b,t}^{P} = 0, \qquad l_{b,t}^{P} = -\left(P_t^I + \frac{\Delta_{re}^{BESS}}{T} + \frac{0.1 \times E_{us}^{BESS}}{T}\right) \rightarrow discharging \tag{31}$$

$$\sqrt[2]{(P_t^2)^{II} + (Q_t^2)^{II}} \leq S_{max}^{inv} \tag{32}$$

Δ_{re}^{BESS} represents the residual BESS capacity from Phase-I, which is distributed over the dispatch time-points equally for Phase-II upper bounds. Additionally, the active power values determined from Phase-I at each point plus 10% of E_{us}^{BESS} are added for Phase-II upper bounds for wider search space and to assure that the total active power handled by the BESS in the real-time phase will not exceed the BESS capacity.

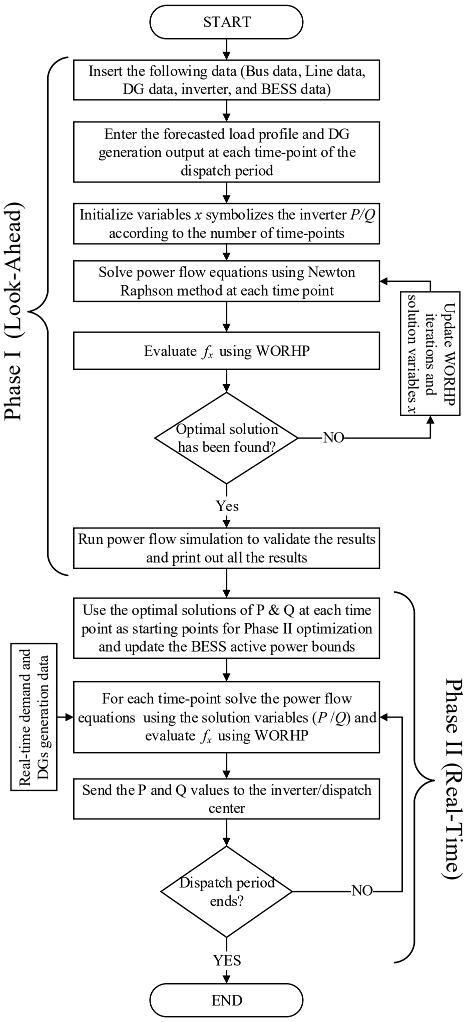

Fig. 2. Proposed model predictive control flowchart

4 Simulated Scenarios and Results

The proposed MPC is applied to an 11 kV 53-node suburban DN located in Northern Ireland shown in Fig. 3, representing a typical distribution network in the UK and Europe. Northern Ireland is facing an energy evolution due to increasing power generation from renewable energy resources in addition to increasing the deployment of electric vehicles and heat pumps. An aggregated generating unit (AGU) located at bus 13 and a lithium-ion BESS is assumed to be installed at bus 49. In Northern Ireland, the DSO aims to incentivize third party BESS owners to locate their units in specific sensitive locations to violations [8]. In this paper, the BESS location and size were determined with the help of a previous study aimed to place BESS based on the sensitive locations exposed to violations (voltage and cable overloading) due to the future uptake of low carbon technologies for this network [9]. The objective of the allocation algorithm was to find the optimal BESS location and size that solves all network violations with minimum BESS size by conducting time-series optimal power flow using swarm-based optimization algorithms. The specifications of the BESS and inverter are tabulated in Table 1. Different cases were simulated to investigate the effectiveness and robustness of the proposed methodology. The initial demand and AGU power profiles were obtained from actual measurements provided by the DSO on the 28th February 2019 (hr 17:00).

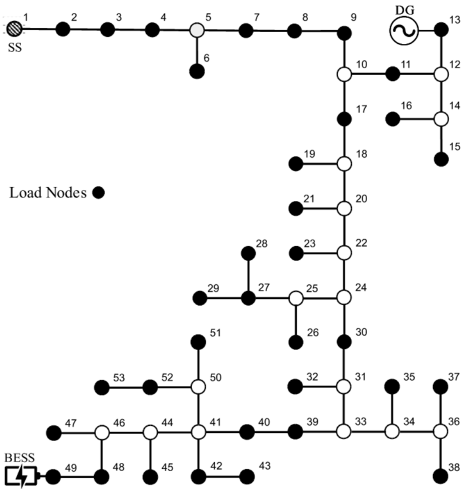

Fig. 3. 11 kV 53-node test distribution network

Table 1 BESS, Inverter Specification, and dispatch horizon details

BESS Rating / Inverter Size	400 kWh / 400kW / 500 kVA
SoC_{max} / SoC_{min} / R_h	90% / 10% / 100%
Usable BESS Capacity	320 kWh
BESS Capacity at Phase-I	288 kWh (90%)
Dispatch Horizon/ Time Step	60 minutes / 5 minutes
Number of time-points/ Variables	12 / 24 (12 *P* – 12 *Q*)

4.1 Case I (charging mode)

This case simulates the starting of an AGU of 4 MW. Based on the look-ahead forecasted data, no violation will occur. Hence, Phase-I schedules the BESS power to optimize the voltage, power factor and losses by operating the inverter on the second P-Q quadrant as shown in Fig. 4 (a). During the real time, the demand decreased suddenly and the ramping of the AGU caused voltage violations at the nodes around the AGU during three time-points. The proposed MPC managed to solve these violations using Phase-II through adjusting the inverter setpoints in real time by absorbing reactive power using the inverter as shown in Fig. 4 (b). Additionally, during the other time-points, Phase-II optimized the power factor and losses.

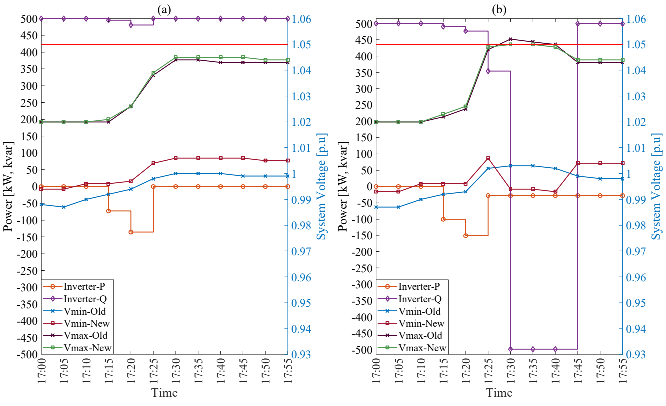

Fig. 4. Case I: (a) Look-Ahead (Phase-I), (b) Real-Time (Phase-II)

As shown in Fig. 4 (b), the proposed MPC has the capability to overcome the forecasted uncertainties on a real-time basis by controlling the inverter power efficiently. The execution time of Phase I was 44 seconds while the total execution time for Phase-II was 11.12 s, or 0.92 s for each time-point.

4.2 Case II (discharging mode)

This case simulates the sudden tripping of the AGU that may occur due to many reasons (e.g. Fault). The AGU capacity was used to keep the system operation within the safe limits during the peak period. Thus, as a consequence of the trip, the voltage goes below 95% for 20 nodes during 5 time-points (25 minutes) until the AGU was connected again at hr 17:50. During the look-ahead phase, the AGU was operating normally and the network operation was not violated according to the forecasted data. Thus, it can be observed that the results from MPC Phase-I optimized the overall network performance as shown in Fig. 5 (a). While during real-time operation, Phase-II intervened to solve the voltage violations that occurred due to the AGU tripping as shown in Fig. 5 (b).

As shown in Fig. 5 (b), MPC Phase-II managed to solve the under-voltage violations successfully by injecting active power from the BESS. This was achieved with a rapid execution time (total 6.4 s and 0.53 s for each time-point). Additionally, the proposed methodology aims to solve the violations while improving other objectives in order to maximize the exploitation of the BESS and inverter as given in Table 2. Table 2 shows the optimal active/reactive setpoints obtained from the proposed MPC Phase-II in addition to the values of the system voltage (minimum/maximum), power factor and line losses before and after the inverter injections.

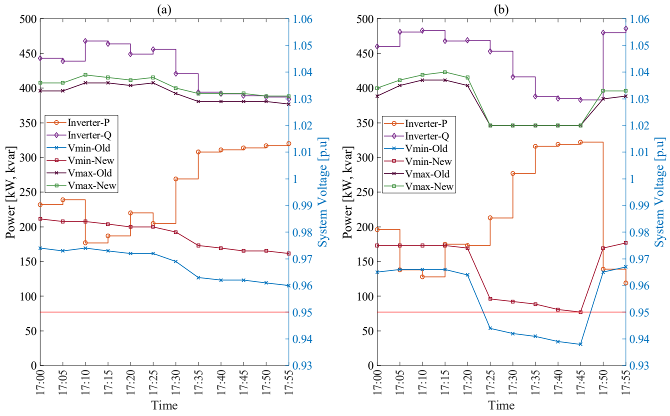

Fig. 5. Case II: (a) Look-Ahead (Phase-I), (b) Real-Time (Phase-II)

4.3 Case III (compensation mode)

In this case the active power of the BESS cannot be used, for example, due to maintenance or empty capacity. This case shows the effectiveness of the inverter in providing reactive power support to the distribution network. This case includes an overvoltage violation caused by reverse power flow. Based on the forecasting, the PV installed on the low voltage network will export power to the gird causing negative *PF* at the substation node and the network constraints are not violated.

Phase-I optimized the network power quality by injecting the required reactive power to optimize the *PF* and losses. Furthermore, because of high forecasting errors, the weather changed radically in real-time, which increased the PV generation causing voltage violations during four time-points. Hence, Phase-II determined the optimal inverter reactive power setpoints to solve this issue to improve the network power quality and stability. Fig. 6 illustrates the required action taken by the proposed MPC through controlling the inverter operation by absorbing reactive power during the congested period to solve the voltage issue. Consuming reactive power during these time-points did not improve the *PF* or the line losses. However, the voltage objective is given a higher priority. Moreover, during the other time-points, the proposed MPC optimized the network performance by minimizing the losses and maximizing the *PF*. The execution time of Phase-II was 13 s; 1.08 s for each time-point.

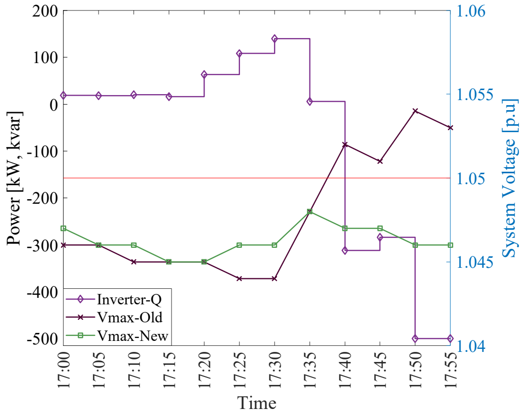

Fig. 6. Case III results: Real-Time (Phase-II)

4.4 BESS Lifetime

The BESS lifetime can be calculated as the relation between the number of cycles and the BESS Depth of Discharge (*DoD*) [10]. The proposed model exploits the BESS by utilizing an optimal combination of active and reactive power setpoints to support the network. Managing both active and reactive power will extend the BESS life as on many occasions, the BESS may not be fully discharged as the reactive power does not depend on the BESS. For the case study, the *DoD* is 80%, however, as explained previously and as given in Table 2, the BESS may not be fully discharged. Hence, it is very difficult to determine the actual number of cycles. However, the minimum number of cycles is determined as 4414 cycles based on the *DoD* value

Table 2 Results Summary for Case II using MPC Phase II (Real-Time)

Time	Inverter (kW)	Inverter (kvar)	PF Old	PF New	PLoss Old [kW]	PLoss New [kW]	Vmin Old [p.u.]	Vmin New [p.u.]	Vmax Old [p.u.]	Vmax New [p.u.]
17:00	196	460	0.836	0.930	162	137	0.965	0.975	1.031	1.034
17:05	138	481	0.784	0.909	174	153	0.966	0.975	1.035	1.037
17:10	128	483	0.775	0.919	183	163	0.966	0.975	1.037	1.039
17:15	175	468	0.818	0.943	185	162	0.966	0.975	1.037	1.040
17:20	173	469	0.816	0.927	186	161	0.964	0.974	1.035	1.038
17:25	213	453	0.971	0.988	228	190	0.944	0.955	1.020	1.020
17:30	277	416	0.976	0.990	251	204	0.942	0.954	1.020	1.020
17:35	316	388	0.976	0.989	256	203	0.941	0.953	1.020	1.020
17:40	319	385	0.976	0.988	272	217	0.939	0.951	1.020	1.020
17:45	322	383	0.976	0.988	278	222	0.938	0.950	1.020	1.020
17:50	139	480	0.780	0.887	162	141	0.965	0.974	1.030	1.033
17:55	119	486	0.764	0.884	156	137	0.967	0.976	1.031	1.033
Total used BESS power [kWh]			210			**Simulation Time [Seconds]**			6.4 / 0.53 s for each time-point	

using the formula in [10]. This number represents the minimum number of cycles assuming that the BESS is fully discharged daily. Small values of *DoD* will extend the BESS lifetime.

5 Conclusions and Discussion

This paper proposed a model predictive control for a BESS installed on the MV DN to improve power quality, stability, and performance. A BESS equipped with an advanced inverter can be operated on all four P-Q quadrants to provide the network with active and reactive power. The proposed MPC consists of two phases; look-ahead and real-time in order to overcome the challenges of forecasting errors by determining precisely the inverter power setpoints that improve the voltage profile, line losses and substation power factor. Real network data, measurements and constraints were used for the case studies. Simulated cases validate the effectiveness of the proposed algorithm in supporting the network with the active/reactive power supply in discharging, charging and compensation modes. The results showed that operating the BESS inverter optimally can solve network challenges.

The proposed MPC employs power flow calculation using the Newton Raphson method which was validated for the test feeder using NEPLAN power system software. Many cases were simulated considering different scenarios that may occur in the distribution network, which proved the durability of the proposed MPC in solving network issues. The simulations were conducted on a 3.2 GHz Intel Core i7-D700 CPU with 16 GB of RAM. The proposed MPC can be adopted by BESS operators due to its effectiveness and short execution time. Wide-range scenarios were simulated and the average time for Phase-I was 71 seconds, and only 20 seconds for Phase-II representing 1.6 seconds for each time-point, which proves its reliability to be implemented online during real-time operation. This time can be vastly decreased using faster processors.

The proposed approach focuses on solving any network violations besides optimizing other aspects through injecting or absorbing active and reactive power by controlling the inverter on its P-Q quadrants. The results highlighted the importance of reactive power control in relieving network congestions. The dispatch horizon can be extended to cover the full day and the proposed MPC can be used for any DN or power system with any number of DGs and buses. The BESS storage capability does not affect the MPC, as the MPC predicts the optimal control setpoints to be delivered by the BESS inverter. Hence, the proposed MPC can accommodate any BESS/Inverter size. Additionally, the MPC model can be modified to accommodate more constraints such as the efficiency and degradation factors. In addition, the objectives of the proposed MPC can be modified according to the operator's preferences to meet the needs of the network, and furthermore, the model can be modified for any type of DG or reactive power compensator thus widening its application.

The proposed MPC can provide the network with different services, these services should be converted into payments to BESS owners with respect to the BESS utilization and availability. In Northern Ireland, the proposed MPC will be worthwhile if the DSO owns the BESS, as at the DN level, there are currently no centrally dispatched distribution system services for DG to support the network. Furthermore, the DSO of Northern Ireland aims to integrate third-party owned BESS to enhance the performance of the distribution networks [8]. However, profitable contracts should be introduced that attracts BESS investors. In reality, BESS owners attempt to increase their revenues by participating in profitable services. The proposed MPC can be applied to aggregated BESS units, according to their availability in return for gainful payments. The need for BESS in modern networks is advantageous to mitigate the challenges imposed from the rapid deployment of low carbon technologies. The proposed MPC is an effective tool that can be used to maximize the utilization of the BESS and the inverter by solving network issues, which supports the secure accommodation of more renewable energy generation as well as decreasing the curtailment. Future work will explore the scalability and robustness of the proposed MPC by integrating other objectives with various dispatch horizons for multiple networks in addition to investigating the efficacy of the MPC on supporting the operation of low voltage networks.

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