Resilient Operation of Power Distribution Systems Using MPC-Based Critical Service Restoration

Preprint

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Resilient Operation of Power Distribution Systems Using MPC-based Critical Service Restoration

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Abstract--**Power distribution systems are more prone to disruptions and cause most power system outages. We propose a service restoration technique to recover the system service (electricity delivery) following an extreme event-triggered substation outage. The proposed technique considers the problem of controlling distributed energy resources (DERs) of a distribution system with the objective of achieving maximum load pick up while satisfying network flow and voltage constraints. The problem is formulated as a model predictive control (MPC), where a linearized optimal power flow (OPF) model is employed to describe the network. The formulation is augmented with a ramping (up) reserve product for the DERs to ensure an upward monotonic load restoration as time evolves. We perform simulations considering the IEEE 13-bus test feeder integrated with wind, solar, microturbine, and energy storage devices. We demonstrate the efficacy of the devised technique in restoring the system loads monotonically, without shedding previously restored loads. We also show the benefit of co-optimization of power and reserve products for DERs on service restoration. In addition, the capability of the technique in regulating nodal voltages and reducing renewable power curtailment is demonstrated.**

Index Terms--**Distribution system, DER, extreme event, service restoration, MPC, OPF, optimization, resiliency, reserve.**

I. Introduction

Incidences of extreme events are rising globally due to the changes in weather conditions and socio-political threats [1]. Data collected by power utilities show that about 90% of power outages in the U.S. initiated from distribution grids [2], [3]. Hence, research efforts have focused on resiliency in the context of distribution grids, see, e.g. [2] - [9]. Most of these studies consider single-step decisions (i.e., no look-ahead) and they did not consider the integration of renewable energy resources (RESs) into the distribution network [9]. Furthermore, the uncertainties from RES power outputs were not managed. Even in the few of studies that considered multi-step decisions to ensure sustainable system resilience over longer operating periods, they did not consider the underlying power flow and voltage constraints of the distribution network [4]. Additionally, none considered the co-optimization of power and reserve products of DERs in the restoration process.

This paper proposes an OPF-driven, ramping reserve-augmented, MPC-based critical service restoration technique for resilient operation of power distribution systems through the control of DERs following the incidence of an extreme event. The service restoration problem is formulated as a look-ahead (multi-step) sequential decision process that employs renewable power forecasts and includes ramping reserve requirements, power flow constraints, and voltage regulation. The effectiveness of the proposed technique is validated using the IEEE 13-bus distribution test system.

The novel contributions of this paper include: 1) application of MPC for load restoration problems with joint formulation of active power balancing, reactive power management, and voltage regulation; 2) co-optimization of power and reserve products of DERs for monotonic load restoration, i.e., no shedding of prior picked up loads, which helps distribution grids sustain electricity supply; 3) shrinking horizon MPC formulation that enables distribution systems effectively utilize their DERs and reduce propagation of uncertainty in the system operation.

The paper is organized as follows. The proposed control framework is presented in Section II. Section III discusses the problem formulation. Section IV presents the simulation results and discussion. The paper conclusion and description of future work are given in Section V.

II. Control Framework

There has been extensive research focus on using MPC for controlling distribution systems containing DERs [10]. The MPC framework proposed in this paper for the service (load) restoration problem has a dynamic control horizon that decreases as time evolves. The system states are updated, and the control problem is solved at each control interval to obtain

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the control actions for the future control intervals. However, only the first control interval action is taken to steer the system, and the rest are discarded. The control period then recedes forward one step and the process rolls until the end of the control horizon. Fig. 1 illustrates the sequential control action execution by the devised MPC with six o'clock outage occurring time, a six-hour initial control horizon (outage duration) and a five-minute control interval [9], [11].

The initial control horizon is set as the restoration time. We assume the restoration time is known.

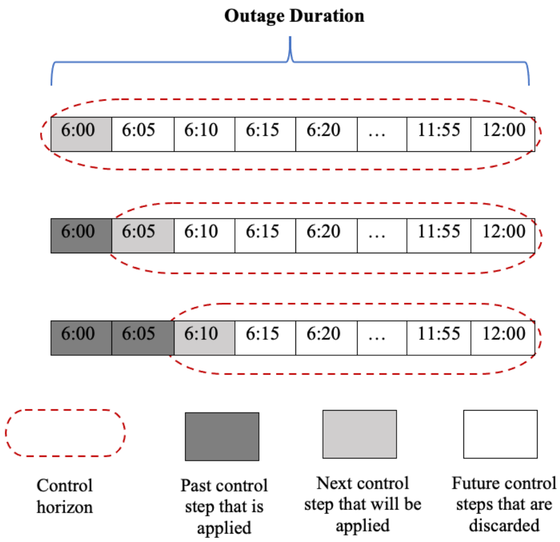

Fig. 1. Sequential control action execution by the devised MPC.

The devised MPC framework contains two cascaded modules, a forecasting module and an optimization module. The forecasting module includes wind and solar power forecasting, while the optimization module solves the control problem and returns control actions based on input information from the forecasting module and other system operating conditions. To obtain updated estimates of renewable generation at each control interval we have implemented simple forecasting methods, employing a 24h-ahead recursive multi-step time series forecasting technique to predict the power output of the wind turbine (WT), and a retrospective method for the PV power forecast (output from the previous day is used to model the output for the next day with an adjustment factor) [9]. In addition, the distribution system contains several spot loads, and we assume constant-power (PQ) load model and constant time series for these loads.

Due to the recent advent of faster (lower latency) communication technologies (such as 5G) and the Internet of Things (IoT) devices, the input data can be passed to the forecasting and optimization modules in the range of few seconds [12] and the decisions can be readily available. The proposed approach can thus be applicable in practice. Besides, while the proposed mixed integer linear program (MILP) may practically be intractable with the size of the network, techniques such as using a coarse time-discretization at later intervals and stopping at a sub-optimal solution should keep the control framework operable within the five-minute control framework, even for larger distribution networks.

The control actions of the devised MPC are the magnitude of load restored (active and reactive), active and reactive power dispatch of the controllable distribution generators (DGs) and energy storage devices (with inverters), and reactive power dispatch and active power curtailment of renewables (with inverters).

III. Problem Formulation

In this section, we present the mathematical formulation of the optimal load restoration problem we aim to solve.

A. *Objective Function*

To guarantee resilient operation of the distribution system, the devised MPC targets to maximize the objective function given in (1). The first summation term of (1) is the total prioritized restored load (active and reactive), the second and third terms are penalties for shedding previously restored loads in the prior time (active and reactive respectively), the fourth summation term is a penalty for not utilizing the system ramping (up) reserve resources to meet the system-wide ramping reserve requirements, and the fifth summation term includes penalties for wind and PV power curtailments.

In (1), N is the number of nodes, T is the control horizon, i is the node index, t is the control interval (time) index, ω is the load priority weight at node i, ψ_P and ψ_Q are the penalties for shedding active and reactive restored loads respectively, ϕ is penalty for matching required and provided reserves, α and β are penalties for wind and solar power curtailments respectively.

$$\begin{aligned}\boldsymbol{Max}: \Bigg\{ & \sum_{i\in N}\sum_{t\in T}\omega_i.\left(P^l_{i,t}+Q^l_{i,t}\right) \qquad (1)\\ & -\psi_P\sum_{i\in N}\sum_{t\in T\setminus\{1\}}\omega_i.max\left(\left(P^l_{i,t-1}-P^l_{i,t}\right),0\right)\\ & -\psi_Q\sum_{i\in N}\sum_{t\in T\setminus\{1\}}\omega_i.max\left(\left(Q^l_{i,t-1}-Q^l_{i,t}\right),0\right)\\ & -\phi\sum_{t\in T}max\left(\left(R_t-\sum_{i\in N}\left(P^{g,raup}_{i,t}+P^{es,raup}_{i,t}\right)\right),0\right)\\ & -\sum_{i\in N}\left(\alpha\sum_{t\in T}P^{wt,cut}_{i,t}-\beta\sum_{t\in T}P^{pv,cut}_{i,t}\right)\Bigg\}.\Delta t\end{aligned}$$

Variables $P^l_{i,t}$ and $Q^l_{i,t}$ are respectively the active and reactive restored loads at node i and time t, R_t is the system-wide ramping (up) reserve requirement at time t, $P^{g,raup}_{i,t}$ is the ramping reserve product of the dispatchable generator g at node i and time t, $P^{es,raup}_{i,t}$ is the ramping reserve product of the energy storage device es at node i and time t, $P^{wt,cut}_{i,t}$ is the wind power curtailed at node i and time t, and $P^{pv,cut}_{i,t}$ is the PV power curtailed at node i and time t. Note that as indicated in Fig. 1 the control horizon T in (1) decreases as the MPC recedes forward in time.

B. *Constraints*

While maximizing (1), the objective function is subjected to the following constraints:

1) Network constraints (LinDistFlow equations):

$$P_{ij,t} = P_{j,t}^{l} - \left(P_{j,t}^{g} + P_{j,t}^{wt} - P_{j,t}^{wt,cut} + P_{j,t}^{pv} - P_{j,t}^{pv,cut} - P_{j,t}^{es,ch} + P_{j,t}^{es,dch}\right) + \sum_{k\in N} A_{jk}\, P_{jk,t}\,, \forall t \in T, \forall j \in N, i = r(j) \quad (2)$$

$$Q_{ij,t} = Q_{j,t}^{l} - \left(Q_{j,t}^{g} + Q_{j,t}^{wt} + Q_{j,t}^{pv} - Q_{j,t}^{es,ch} + Q_{j,t}^{es,dch}\right) + \sum_{k\in N} A_{jk}\, Q_{jk,t}\,, \ \forall t \in T, \forall j \in N, i = r(j) \quad (3)$$

$$V_{j,t} = V_{i,t} - 2\left(r_{ij}P_{ij,t} + x_{ij}Q_{ij,t}\right), \forall t \in T, \forall j \in N, i = r(j) \quad (4)$$

2) Voltage constraints

$$v_{min}^{2} \le V_{j,t} \le v_{max}^{2} \quad (5)$$

$$V_{j,t}(t) = \left(v_{j,t}\right)^{2} \quad (6)$$

$$v_{j,t} = 1\,, \forall t \in T, j = slack\ bus \quad (7)$$

3) Generator power and reserve limits

$$0 \le P_{j,t}^{g} \le P_{j,max}^{g} \quad (8)$$

$$0 \le Q_{j,t}^{g} \le Q_{j,max}^{g} \quad (9)$$

$$0 \le P_{j,t}^{g,raup} \le P_{j,max}^{g} \quad (10)$$

$$P_{j,t}^{g} + P_{j,t}^{g,raup} \le P_{j,max}^{g} \quad (11)$$

4) Generator fuel (total energy production) constraint

$$\sum_{t\in T}\left(P_{j,t}^{g} + P_{j,t}^{g,raup}\right)\Delta t \le E_{j,max}^{g,p} \quad (12)$$

$$\sum_{t\in T} Q_{j,t}^{g}\Delta t \le E_{j,max}^{g,q} \quad (13)$$

5) Restored load limits

$$0 \le P_{j,t}^{l} \le P_{j,t}^{l,demand} \quad (14)$$

$$0 \le Q_{j,t}^{l} \le Q_{j,t}^{l,demand} \quad (15)$$

6) Power factor consistency constraint

$$Q_{j,t}^{l} \Big/ P_{j,t}^{l} = Q_{j,t}^{l,demand} \Big/ P_{j,t}^{l,demand} \quad (16)$$

7) Energy storage power and reserve limits

$$0 \le P_{j,t}^{es,ch} \le b_{j,t}^{es,ch} P_{j,max}^{es,ch} \quad (17)$$

$$0 \le Q_{j,t}^{es,ch} \le b_{j,t}^{es,ch} Q_{j,max}^{es,ch} \quad (18)$$

$$0 \le P_{j,t}^{es,dch} + P_{j,t}^{es,raup} \le b_{j,t}^{es,dch} P_{j,max}^{es,dch} \quad (19)$$

$$0 \le Q_{j,t}^{es,dch} \le b_{j,t}^{es,dch} Q_{j,max}^{es,dch} \quad (20)$$

$$b_{j,t}^{es,ch} + b_{j,t}^{es,dch} = 1\,, b_{j,t}^{es,ch}, b_{j,t}^{es,dch} \in \{0,1\} \quad (21)$$

8) Energy storage state of charge (SOC) limits

$$SOC_{j,min}^{es} \le SOC_{j,t}^{es} \le SOC_{j,max}^{es} \quad (22)$$

9) SOC dynamics

$$SOC_{j,t}^{es} = SOC_{j,t-1}^{es} + \left(\frac{\eta_{j}^{es,ch} P_{j,t}^{es,ch}}{C_{j}^{es}} - \frac{P_{j,t}^{es,dch}}{\eta_{j}^{es,dch} C_{j}^{es}}\right)\Delta t \quad (23)$$

$$SOC_{j,t}^{es} \ge SOC_{j,min}^{es} + P_{j,t}^{es,raup}\Delta t \quad (24)$$

10) Renewable power curtailment limits

$$0 \le P_{j,t}^{wt,cut} \le P_{j,t}^{wt} \quad (25)$$

$$0 \le P_{j,t}^{pv,cut} \le P_{j,t}^{pv} \quad (26)$$

11) Inverter operation

$$-\sqrt{S_{j}^{2} - P_{j,max}^{2}} \le Q_{j,max} \le \sqrt{S_{j}^{2} - P_{j,max}^{2}} \quad (27)$$

12) Reserve requirement

$$R_{t} = c\sum_{j\in N}\left(P_{j,t}^{wt} + P_{j,t}^{pv}\right) \quad (28)$$

where $P_{ij,t}$ and $Q_{ij,t}$ are respectively the active and reactive power flows from node i to node j at time t, $P_{j,t}^{g}$ and $Q_{j,t}^{g}$ are respectively the active and reactive power outputs of the dispatchable generator, $P_{j,t}^{wt}$ and $P_{j,t}^{pv}$ are respectively the wind and solar power forecasts, $P_{j,t}^{es,ch}$ and $P_{j,t}^{es,dch}$ are respectively the charging and discharging power of the energy storage device, $Q_{j,t}^{wt}$ and $Q_{j,t}^{pv}$ are respectively the reactive power injections/absorptions of the wind turbine converter and PV inverter, and $Q_{j,t}^{es,ch}$ and $Q_{j,t}^{es,dch}$ are respectively the reactive power absorption and injection by the energy storage device converter, A is an adjacency matrix which represents the grid topology, A_{ij} is 1 if node i is the root node of node j and 0 otherwise, r_{ij} and x_{ij} are respectively the resistance and reactance of the line from node i to node j, $v_{j,t}$ is the node voltage, v_{min} and v_{max} are respectively the lower (LB) and upper (UB) bounds of the node voltages, $P_{j,max}^{g}$ and $Q_{j,max}^{g}$ are respectively the rated active and reactive power of the generator, $E_{j,max}^{g,p}$ and $E_{j,max}^{g,q}$ are respectively the allowable peak total active and reactive energy productions associated with fuel availability, Δt is the length of one control interval, $P_{j,t}^{l,demand}$ and $Q_{j,t}^{l,demand}$ are respectively the active and reactive power demanded prior to the extreme event, $P_{j,max}^{es,ch}$ and $P_{j,max}^{es,dch}$ are respectively the maximum charging and discharging power limits of the energy storage, $Q_{i,max}^{es,ch}$ and $Q_{j,max}^{es,dch}$ are respectively the maximum reactive power absorption and injection by the energy storage device inverter, $b_{j,t}^{es,ch}$ and $b_{j,t}^{es,dch}$ are binary variables indicating the status of the energy storage and take a value of 1 respectively if the energy storage is charging and discharging at time *t*, and 0 otherwise, $SOC_{j,t}^{es}$ is the SOC of the energy storage, $SOC_{j,min}^{es}$ and $SOC_{j,max}^{es}$ are respectively the allowable minimum and maximum SOCs of the storage, $\eta_{i}^{es,ch}$, $\eta_{j}^{es,dch}$ and C_{j}^{es} are respectively the charging efficiency, discharging efficiency and rated storage capacity of the storage, S_{j} represents the rated capacity (apparent power) of the generators and inverters, and c is the ramping reserve requirement coefficient, at node j and time t.

We reformulated the "max" penalty terms in the objective (1) with proper slack variables and obtained its convex version. Therefore, together with constraints (2) – (28) the formulated problem is a mixed integer linear program (MILP) and open-source MILP solvers can be leveraged to obtain (near) global solution to the problem. The decision variables are thus: $P_{ij,t}$, $Q_{ij,t}$, $P^{l}_{j,t}$, $Q^{l}_{j,t}$, $P^{g}_{j,t}$, $P^{g,raup}_{j,t}$, $Q^{g}_{j,t}$, $P^{es,ch}_{j,t}$, $Q^{es,ch}_{j,t}$, $P^{es,dch}_{j,t}$, $P^{es,raup}_{j,t}$, $Q^{es,dch}_{j,t}$, $Q^{es,dch}_{j,t}$, $SOC^{es}_{j,t}$, $b^{es,ch}_{j,t}$, $b^{es,dch}_{j,t}$, $P^{wt,cut}_{j,t}$, $Q^{wt}_{j,t}$, $P^{pv,cut}_{j,t}$, and $Q^{pv}_{j,t}$.

IV. RESULT AND DISCUSSION

To demonstrate its effectiveness, we apply the proposed MPC-based service restoration method to the IEEE 13-bus distribution test system with integrated wind turbine (WT), photovoltaic solar (PV), microturbine (MT) and energy storage (ES) device, as shown in Fig 2. We call this system as the *case study system,* henceforth. We consider nine spot loads ($L_1 - L_9$) with constant power load models. We assume an extreme event-caused substation outage, shown in Fig. 2, that occurred at time $t = t_0$ and the system is then seamlessly switched to islanded operation. The utility outage time is set as six hours. The system parameters are given in Table I.

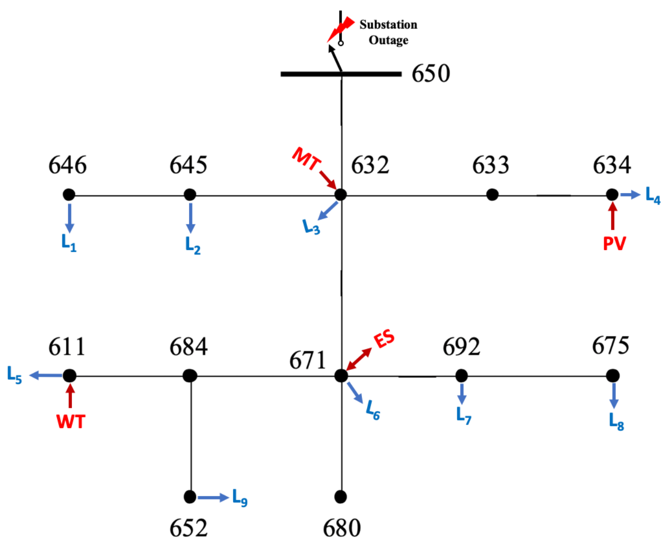

Fig. 2. Modified IEEE 13-bus system with DERs.

TABLE I
SYSTEM PARAMETERS

Parameter	Value	Parameter	Value
ω	[1.0, 1.0, 0.9, 0.85, 0.8, 0.65, 0.45, 0.4, 0.3]	T	6h
α	0.2	Δt	1/12
β	0.2	P^{g}_{max}	300kW
ψ	100	S^{g}	350kVA
ϕ	50	$E^{g,p}_{max}$	1000kWh
$P^{l,demand}$	[115, 85, 49.75, 200, 85, 199.75, 85, 324, 64] kW	$E^{g,q}_{max}$	750kvarh
$Q^{l,demand}$	[66, 52, 29, 115, 40, 109, 45, 141, 43] kvar	$P^{es,ch}_{max}$	200kW
t	[1, 2, …, 72]	$P^{es,dch}_{max}$	200kW
WT rating	150kW	$S^{es,inv}$	250kVA
PV rating	300kW	SOC^{es}_{0}	90%
C^{es}	800kWh	SOC^{es}_{min}	20%
LB, UB	0.95, 1.05pu	SOC^{es}_{max}	100%
$\eta^{es,ch}$	95%	$\eta^{es,dch}$	90%

We implemented the MPC using JuMP [13] in Julia 1.5 and the renewable power forecasting, data analytics and the execution of the MPC were implemented in Python 3.7. The computation was performed on a Mac Pro with Intel Core i7 Quad-Core Processor (2.80GHz) and 16GB RAM, and the problem was solved by the GLPK open-source solver.

We discuss the simulation results obtained from our experiments based on the following three cases:

- *Case I*: System operation without reserve;
- *Case II*: System operation with different levels of reserve requirements;
- *Case III*: System operation under renewable shortfall and over-generation.

Figs. 3 through 5 show the operation of the system in Case I following the occurrence of the extreme event at $t = t_0 = 12:00$ on a specific day (August 3, 2019). Fig. 3 illustrates the active and reactive power dispatch and total restored load. Fig. 4 shows the active and reactive individual restored loads. Fig. 5 depicts the node voltages.

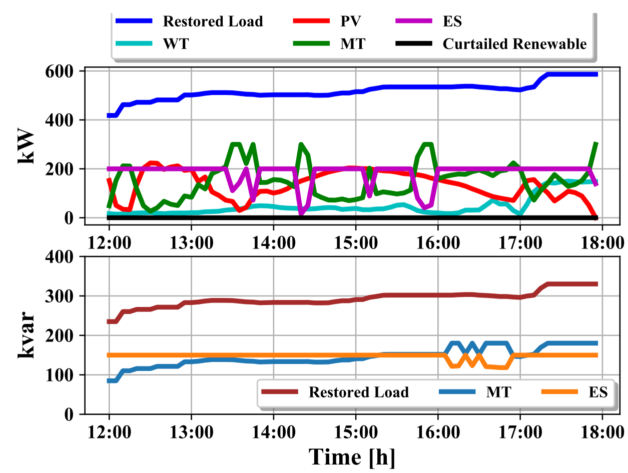

Fig. 3. Active (kW) and reactive (kvar) power dispatch and load restoration.

As shown in Fig. 3, the MPC operates the DERs interactively to restore the distribution system load after the substation outage. The MT and ES sometimes operate complementary and produce their rated power when the renewable production is low. It is also shown in Fig. 3 that the MPC manages to utilize all the available renewables without curtailment.

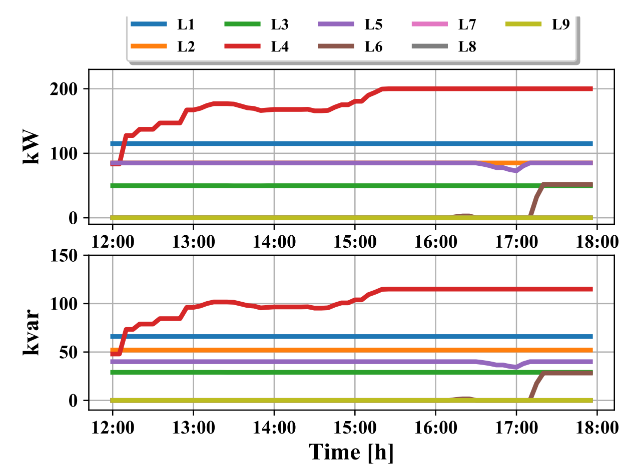

Fig. 4. Restored loads (active and reactive).

We only set the MT and ES inverter to inject/absorb reactive power. It is seen in Fig. 3 that the reactive power production from the MT and the ES inverter restores the reactive power demand of the system.

In addition, as we observe from Fig. 3, the total active (kW) and reactive (kvar) restored loads follow the same pattern as the control time evolves due to the power factor consistency constraint we imposed in (16). However, the restored load is not upward monotonic, there is shedding of previously restored load as it is observed in Fig. 3 in the periods 13:30–14:00, 14:20–14:40 and 16:20–17:05. This problem can be addressed by augmenting reserve product to the MT and ES power products and will be discussed in this section in Case II results.

As illustrated in Fig. 4, the first 3 higher priority (critical) loads ($L_1 – L_3$) were picked up with their full demand (100%) throughout the control horizon. However, the lower priority loads (L_4 - L_6) were not served with their full demands except in some control steps. The lowest priority loads ($L_7 – L_9$) were not served at all. This shows the efficacy of the proposed restoration technique for picking up the critical loads first when extreme event causes power deficiency in a power system.

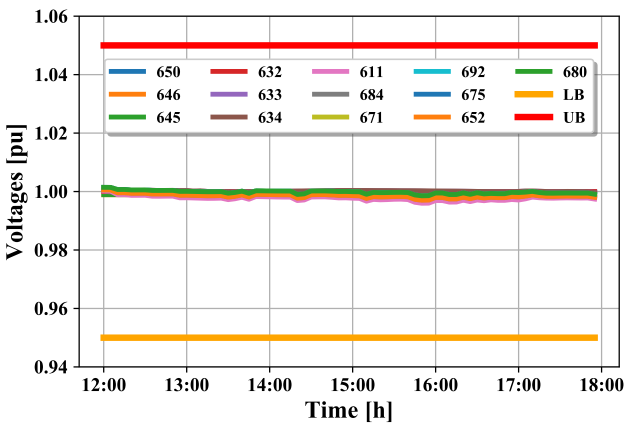

Fig. 5. Nodal voltages.

As shown in Fig. 5, the MPC's linearized power flow model is able to regulate the system node voltages well-within the allowable ANSI's low-voltage distribution grid voltage range 0.95 to 1.05 pu. While this model is an approximation, it is likely the voltages would be within limits should the set-points be implemented in a physical system.

The operation of the system in Case II, with varying levels of reserve requirement, is demonstrated in Fig. 6. It is shown that as the system-wide reserve requirement c increases, the aggregate restored load becomes more upward monotonic and there does not exist any shedding of previously restored load. As clearly seen in Fig. 6, the restoration curve with the highest value of reserve requirement (c=75) restored the loads conservatively with consideration of monotonic increase as time evolves. This confirms the benefit of having reserve in the system to ensure the restoration is sustainable without shedding previously restored loads.

The system operation with under-forecasted (2019-08-04 10:00 - 2019-08-04 16:00) and over-forecasted (2019-08-02 00:00 - 2019-08-02 18:00) renewable power production, Case III, is depicted in Fig. 7.

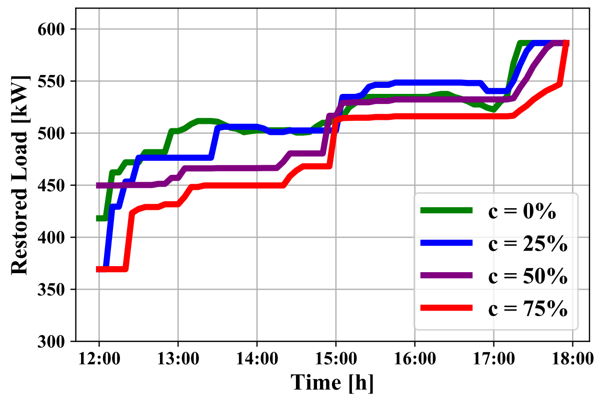

Fig. 6. Impact of ramping reserve level on load restoration.

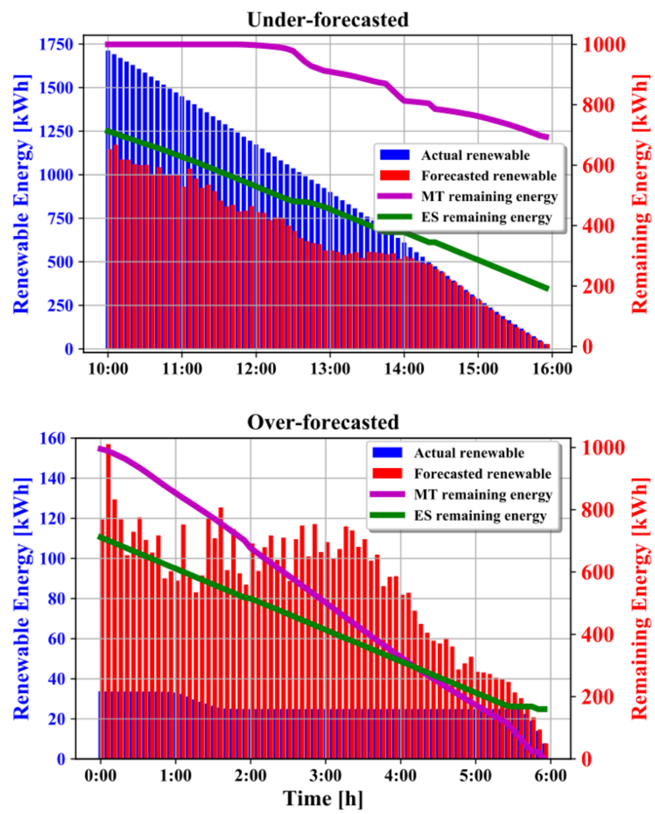

Fig. 7. Impact of renewable uncertainty on resource utilization.

As we observe from Fig. 7 with under-forecasted (forecast < actual) renewable (wind + solar) case the MPC does not utilize all the available fuel of the MT and the stored energy in the ES. This is due to the MPC initially expecting that the system has less renewables and but later on realizing that this is not true and prefers to use the available renewable instead of feeding the system from the MT and ES. On the other hand, during the over-forecasted (forecast > actual) renewable case, the MPC uses all the available fuel of the MT (remaining energy = 0kWh at t=6:00) and stored energy of the ES (min SOC = 20% = 160kWh at t=6:00). This is because initially the MPC expects the system has more renewable generation available but later on in real-time it realizes that this is not true and forced to feed more energy from the available MT and ES to restore more loads. Note that the renewable energy production at each time step is total energy production through the control horizon starting at that step but with shrinking length as the MPC horizon. These findings in Case III confirm the importance of MPC-based restoration approach in handling the uncertainty of renewables through real-time realization and decision adjustment capability, and also demonstrate the potential of reserved energy to address such operational uncertainties.

V. Conclusion and Path Forward

Resiliency have become a vital property of critical systems and communities. To improve the resiliency of distribution systems against extreme events, we proposed an MPC-based service restoration technique and demonstrated its effectiveness using the IEEE 13-bus distribution test system with DERs. Our findings reveal that deployment of DERs and adopting robust distribution grid automations (such as automatic and critical service restoration algorithms) play significant roles in improving the resilience of power systems against extreme events. Our current research findings and capabilities will continue in the next phases of our research such as consideration of more complex power networks and advanced stochastic formulations to address the uncertainty of service recovery time and renewables.

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