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APPLIED RESEARCH

Power System Frequency Control Architecture Combining Open Charge Point Protocol and Electric Vehicle Model Predictive Charge Rate Control

KENTA KIRIHARA^{1,2}, (Member, IEEE), AND TOHRU KAWABE³, (Member, IEEE)

¹Graduate School of Systems and Information Engineering, University of Tsukuba, Tsukuba 305-8577, Japan

²Research and Development Group, Hitachi Ltd., Ibaraki 319-1292, Japan

³Division of Information Engineering, Faculty of Engineering, Information and Systems, University of Tsukuba 305-8577, Tsukuba, Japan

Corresponding author: Kenta Kirihara (s1830145@s.tsukuba.ac.jp)

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ABSTRACT This research proposes a power system frequency control architecture which leverages Open Charge Point Protocol—a rising open-source protocol for charge rate control of electric vehicles. Unlike conventional research that focused on building a high-performance controller, this research puts emphasis on the ease of deployment. Specifically, this research explores the design of a frequency control architecture around the basic functionality of an open-source protocol while allowing substantial performance without the need for a well-tuned specialized protocol. As the usage of open-source protocols cannot provide a quick response, the proposed architecture alleviates this limitation by (a) utilizing a hierarchical structure to emulate a faster control interval and (b) providing a model predictive controller with system integrity protection scheme behavior to have sufficient performance under both large and small disturbances. The overall architecture is evaluated against an aggregated power system frequency response model on Simulink for both large and small disturbances. Compared to a tuned proportional integral derivative controller on the same architecture, the proposed architecture observed an average reduction of 21.77% in nadir in the step disturbance test and an average reduction of 36.27% in standard deviation from the nominal frequency in the load variation test.

INDEX TERMS Electric vehicles, vehicle-to-grid, optimization, frequency.

NOMENCLATURE

C	Number of control groups.	A_d, B_d, C_d	Discretized internal model of MPC.
$u^{ev}[t]$	Control signal of the central controller at t .	P, C	Plant and controller blocks in an abstract power system model.
$u_c^{ev}[t]$	Control amount of c th EV control group at t .	a_j, b_i	Coefficients to the aggregated transfer function.
Δt	Control interval.	d	Disturbance.
T_{ev}	EV response delay.	u^{min}, u^{max}	Lower and upper bounds of MPC.
$y[k]$	Output signal for MPC at k th control step.	$p_{char}^{max}, p_{char}^{min}$	Combined maximum/minimum charging rate of all EVs.
$u[k]$	Control signal for MPC at k th control step.	P_{char}	Base charge rate.
N	Prediction horizon of MPC.	N_{ev}	Number of EVs.
r	Weighing factor for MPC.	SoC_{max}	Maximum State-of-Charge.
		SoC_0	Initial State-of-Charge.
		S_{base}	System base.
		η_c	Charge efficiency.

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t_c	Time necessary for charge completion.
f_{sips}	SIPS threshold for frequency.
d_{sips}	SIPS threshold for disturbance size.
$u^{max,sips}$	Upper bound of MPC when SIPS is active.

I. INTRODUCTION

A. BACKGROUND

With accelerating decarbonization, massive quantities of electric vehicles (EVs) and renewable energy sources (RES) are expected to enter the power system in the coming years. However, replacement of traditional generation with RES, combined with variation originating from both RES and EVs, has brought about concerns in maintaining power system frequency—one metric that is difficult to control through investing in traditional power system network components. Concern over power system frequency have been gaining focus with the prevalence of frequency related blackouts such as the Hokkaido blackout of 2018 in Japan. As a response to this rising concern over power system frequency, utilization of EVs in load frequency control (LFC) have also been gaining attention.

B. LITERATURE REVIEW

EVs in LFCs have been researched for approximately two decades, where majority of the significant research started to emerge in the last 10 years. Early research focused to resolve fundamental issues such as state-of-charge (SoC) management or performance of LFC without considering timeframes such as primary or secondary frequency control. For instance, [1] is one of the significant early works which addressed LFC while maintaining SoC. Other key research from this era have also laid the foundation of EVs with LFC. These include hierarchical model predictive controller (MPC) [2], fuzzy controller [3], robust proportional integral controller by using a H2/H ∞ control approach [4], and use of distributed functional observers [5]. [1], [2], [3], [4], [5] have laid the foundation for the modern EV-based LFC, where variants have been proposed based off of these work.

As the value of utilizing EVs in LFC became apparent, research started to expand into specific issues. For instance, designing specific controllers for different time frames, primary (short-term) and secondary (medium-term), became popular. Primary control included frequency droop controllers [6], mixed hierarchical control between traditional generation and EVs [7], Imperialist Competitive Algorithm (ICA) tuned MPC [8], user selectable vehicle-to-grid (V2G) schemes [9], and controllers mixed with high-voltage direct current (HVDC) lines [10]. Generally, research in this timeframe focused on building a high performing controller and control architecture to maximize the system's resistance against large disturbances. On the other hand, for secondary control, [11], [12], [13] proposed variations of fuzzy control. Research in this timeframe focused mainly on combatting

smaller disturbances, hence applying a less rigorous controller. Other research continued to focus on specific issues such as SoC maintenance [14], performance of LFC [15], battery degradation cost [16], or even time delay [17], [18]. [19] was especially significant since the actual control time delay of EVs in frequency control was field tested.

Despite alternative architectures existing, research have continued to develop around a hierarchical architecture. Although an explicit reason has not been stated, the simple to implement structure of hierarchical architectures, as opposed to distributed architectures that require measures to preventing hunting oscillations, may have led to an interest in pursuing hierarchical architectures. Research such as [20], [21] utilized a hierarchical architecture due to the intuitive implementation. On the other hand, research relating to controllers have yet to reach a single consensus. According to the recent work of [22], most controllers fall under an integral order, fractional order, intelligent, or cascaded structure. Of which, fractional order and intelligent controllers have been popular.

Fractional order controllers have been gaining attention with the added ability to better tune than traditional integral order controllers due to the fractional order terms. One drawback is in determining the optimal parameters for such controller, and research such as [22], [23], and [24] have proposed variants of fractional order controllers using different tuning methods. Unlike proportional integral derivative (PID) controllers, which is simple to tune, the current state of tuning fractional order controllers relies on metaheuristic methods.

All three subsets of intelligent controllers (fuzzy, neural, and others according to [22]) are still researched. For instance, [25] and [26] proposed variants of fuzzy proportional integral (PI) controllers. Furthermore, recent advancements in artificial intelligence led to the introduction of reinforcement learning based controllers [27], [28], and long-short term memory (LSTM) and deep neural network (DNN) based controllers [29]. Despite the long history of MPC in EV-inclusive LFC, MPC still continues to be well researched as seen in [30], [31], and [33]. Other types of controllers, such as static output feedback controller based on refined-Jensen inequality [34] and event-triggered controllers [35], [36] have also proposed in the recent years.

C. RESEARCH GAP AND CONTRIBUTIONS

The past decade has shown that various controllers are effective in stabilizing the power system frequency with EV charge rate control. Adaptive, droop, MPC, fuzzy, PID controllers have all observed a sufficient performance. Even elementary control schemes such as outlined in [37] was adequate to show that benefits exist.

As LFC utilizing EVs became widely known, real-life application has been gaining traction. The Parker Project in the Danish grid explored the viability of ancillary services, protocols, and scalability through a field test [46]. The study concluded that ancillary services currently considered in the Danish grid is possible using EVs, V2G capabilities works well for certain subset of EVs, and scalability in functions in

accordance with Market Model 2.0 was feasible [46]. However, the study also found that Open Charge Point Protocol (OCPP) with certain chargers exhibited delays of several seconds to respond to control signals. Similarly, as part of the Kansai Virtual Power Plant (VPP) Project in west Japan (Kansai), LFC using EVs, and battery resources were also verified to be effective for both governor free equivalent and LFC regardless of the communication channel utilized (dedicated or encrypted IP) [47]. According to [47], the use of a single vendor (closed protocol) mixed in with other battery resources have shown to be adequate to follow LFC control signals.

Overall, through these field studies, the viability of LFC is indisputable; however, to achieve a cost-scalable and deployable solution remains a challenge. The use of commercial internet, which is far more economical than dedicated lines, is viable as [47] reported. Such use of commercial internet would require a certain level of standardized protocols. One rising standardized protocol is OCPP, which is a front-end (charger to aggregator) protocol that is compatible across different charging stations with varying chargers (CHAdeMo, ISO 61851 PWM, etc.). The challenge is the inherent delay of introducing such front-end protocol would have which can lead to reduced performance of the overall LFC.

Given the above discussion, the motive of this research is to design a practical frequency control architecture based on OCPP to offer sufficient performance. Hence, the specific contributions of this research are:

- 1) A frequency control architecture characterized by an asynchronous hierarchical structure. This allows a more granular control signal even while using OCPP.
- 2) A model predictive controller to acts as the central controller within the architecture. The model predictive controller incorporates a system integrity protection scheme (SIPS) behavior to allow better protection against both small and large disturbances

II. PROBLEM FORMULATION

A. POWER SYSTEM MODELING AND FREQUENCY CONTROL

Power system frequency refers to the fundamental frequency of the sinusoidal voltage waveform. In transient-states, power system frequency differs throughout the system; however, since this research is on LFC, which has time ranges several orders higher than transient, frequency is assumed to be the consistent throughout the system like most studies.

With such assumption, Fig. 1 models the power system for this research. The general model is based on [37], where the power system frequency deviation (in per-unit) occurs as result of the total power mismatch (i.e., difference between generated and consumed power). The model considers all relative support from EVs (reduction or increase in charging rate) as an extra electrical power injected into the system. For more details on the model, refer to [37].

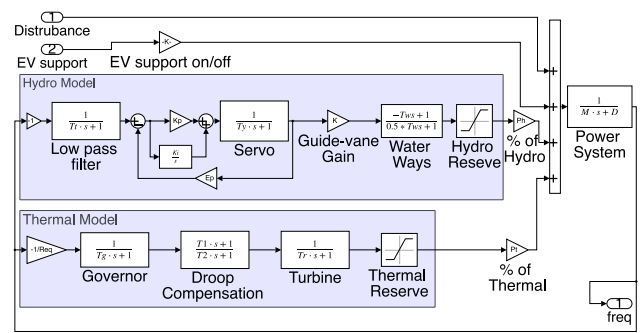


FIGURE 1. Power system model assumed in this research based on [37].

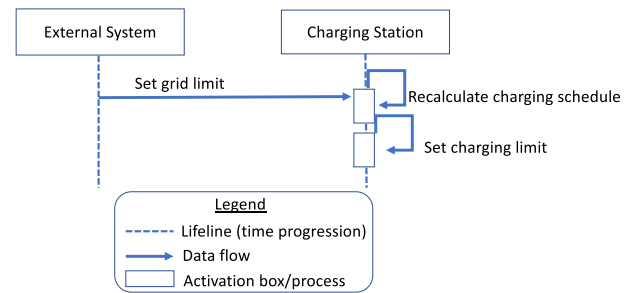


FIGURE 2. Example of modifying the charge rate through OCPP [38].

B. OPEN CHARGE POINT PROTOCOL

OCPP is one of the latest smart charge protocols for EVs developed by Open Charge Alliance. One of the recent versions, at the time of this research, is version 2.0 with bi-directional (charging and discharging) capabilities [38]. The protocol allows for remote charging rate control, as well as other capabilities such as transaction management. Due to flexibility of the protocol, large amount of EVs may utilize OCPP or variant of OCPP soon. Even legacy standards such as ChaDeMo developed in Japan, are currently working to harmonize [39].

Fig. 2 exemplifies the charge rate limit control through OCPP as defined in the specification [38]. The external system (such as an Energy Management System) sets a grid limit to the charging station. Once the charging station receives the grid limit signal, the charging station recalculates the charging schedule to enforce the limit. However, since there is a delay time between setting the grid limit (charging limit specified from an external system) and implementing the actual charging limit, altering the limit frequently is difficult.

Although not explicitly specified, if the external system sends a new grid limit while the controller calculates the previous limit, the effects of the new grid limit may not take effect until the charge point imposes the previous limit. This proposes a unique challenge to utilizing EVs using charge rate limit control through OCPP: frequently adjusting charge rate is not possible; hence, many of the control schemes of the past research cannot be applied directly. For instance, if grid limit alteration requires 2 seconds to take effect on all EVs, the

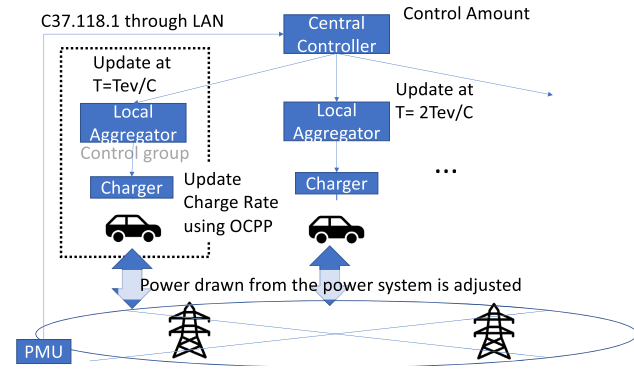


FIGURE 3. Overall architecture.

minimum control interval would be 2 seconds as well. [46] implicitly observes this limitation.

Although this does not propose an extreme consequence during large disturbances, where substantial amounts of support from EVs in a brief time is necessary, this limitation could be crucial for smaller disturbances such as net load variations. As a response to this limitation, the next section proposes a frequency control architecture as a remedy.

III. FREQUENCY CONTROL ARCHITECTURE

A. OVERVIEW

Fundamentally, control delays associated with EVs are unresolvable through an architecture; however, using an asynchronous approach can resolve challenges in control intervals.

Fig. 3 visualizes the proposed architecture. The following summarizes the sequence of operation:

- 1) A C37.118.1-2014a compliant PMUs measure the power system frequency and power. PMUs measure frequency with high accuracy: within 0.01 Hz error even under dynamic conditions [40].
- 2) The central controller determines the amount of EV support needed at the control timing.
- 3) The central control calculates an updated charge limit and sends to the local aggregators.
- 4) The local aggregators send the charge limit to each charging point.
- 5) Each charging point adjusts the charge rates to provide frequency support to the power system.

The key characteristic of the proposed architecture is the asynchronous use of local aggregators. As highlighted earlier, the challenge of using OCPP is the large control interval. The proposed architecture resolves this challenge, by controlling aggregated EV groups asynchronously to emulate a shorter control interval. Given C control groups, the following steps overviews the control signal calculation:

- 1) Calculate the new control signal $u^{ev}[t]$.
- 2) Calculate and send the new control signal $u_c^{ev}[t]$ to the c th control group.

- 3) Reschedule the charge rate of the c th control group based on $u_c^{ev}[t]$.
- 4) Increment t by Δt and repeat the process.

In the above process, the following calculates Δt :

$$\Delta t = T_{ev}/C \quad (1)$$

Note, due to the excessive burden discharging adds onto the battery (see [42] for details), regardless of the type, this research only considers charge rate control despite OCPP is compliant with V2G functions.

B. CONTROL SIGNAL TO EACH CONTROL GROUP

When the control logic calculates the total EV support necessary, the EV control group cannot directly respond. Given a control signal $u^{ev}[t]$ from the central controller, the following calculates the effective control signal for the c th control group ($u_c^{ev}[t]$):

$$u_c^{ev}[t] = u^{ev}[t] - u^{ev}[t - \Delta t] + u_c^{ev}[t - \Delta t] \quad (2)$$

C. SELECTION OF A HIERARCHICAL ARCHITECTURE

There are several architectures that can be implemented using OCPP. Hence, it is crucial to address the alternatives to understand why a hierarchical architecture is suitable for this application.

One possible architecture is the complete removal of the local aggregators: making a N:1 connection between the charging points and the central controller. In theory, this architecture would be simple and easy to implement, however, would require the central controller to communicate with massive amount of charging points. This proposes a design challenge where (a) communication losses, (b) delayed control signals, or (c) higher likelihood of failure for the central controller can occur due to the overburden. Therefore, removal of the local controllers is not preferable.

Another possible architecture is the complete removal of the central controller instead, shifting to a distributed architecture. Such architecture requires communication between the local controllers to communicate the previous control actions. To effectively communicate the previous control actions, if necessary, the control interval must be longer than the communication delay between the local controllers. On the other hand, hunting oscillations could potentially be an issue in a non-cooperative distributed architecture. For this reason, a distributed architecture is also not appropriate for use with OCPP.

The hierarchical architecture proposed in this research mitigates and remedies the challenges of the alternative architecture by splitting the number of connections between the local aggregators. If there are N_{ev} EVs in total and C control groups, the total number of connections at the central controller reduces to C , and at each local controller reduces to $1 + N_{ev}/C$. Furthermore, because the central controller already has the previous control signal, this architecture also mitigates the control interval limitation of a fully distributed approach.

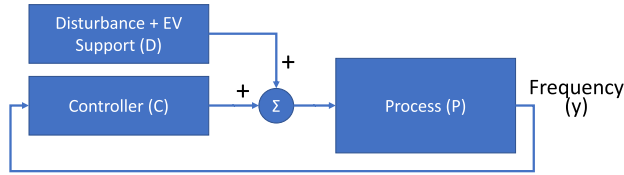


FIGURE 4. Abstract representation of the power system.

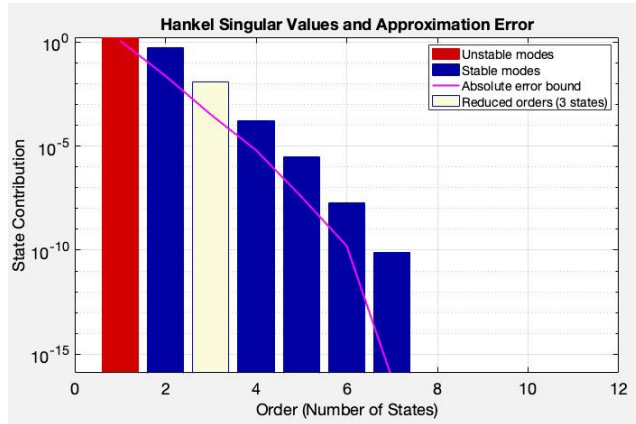


FIGURE 5. An example of model reduction using Hankel singular value in MATLAB.

D. DESIGN LIMITATION OF THE ARCHITECTURE

The number of control groups is a crucial parameter which can alter the performance of the proposed architecture. Less control groups can respond to larger disturbances better if they occur at the right timing but cannot respond to disturbances that occur moments after the previous control signal.

Having more control groups intuitively point to better overall performance; however, the reporting interval of PMUs limit the maximum number of control groups. Without measured feedback from the power system, shorter control interval brings no extra benefits. Considering the maximum reporting rate of commercial PMUs are four times the nominal power system frequency (e.g., 200/240 reports per second for 50/60 Hz) [41], the theoretical limit on the number of effective control groups is 200/240 respectively. Though, 50/60 reports per second as defined in C37.118.1-2014a may be a practical limit. To remedy these limitations, a performance-driven controller is necessary in the central controller. The next section outlines a design of MPC with SIPS.

IV. MODEL PREDICTIVE CONTROLLER WITH SYSTEM INTEGRITY PROTECTION SCHEME

A. OVERVIEW OF MODEL PREDICTIVE CONTROLLER

MPC is a widely utilized controller which computes an optimal control sequence for a predicted horizon every control interval. Because the controller computes the optimal control sequence using an optimization engine, efficient utilization of control targets is possible. The following shows one example

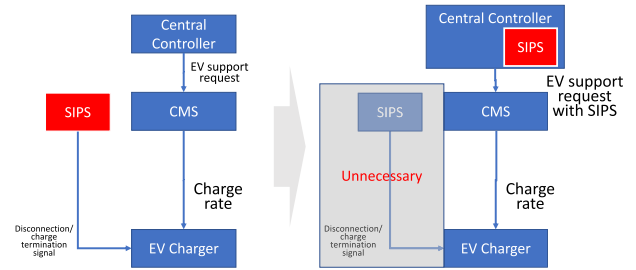


FIGURE 6. Incorporation of SIPS behavior into the central controller.

of a state based MPC:

$$\begin{aligned}
 \min \quad & \sum_{k=t+\Delta t}^{t+N\Delta t} (y[k])^2 + r(u[k] - u[k-1])^2 \\
 \text{s.t.} \quad & u^{\min} \leq u[k] \leq u^{\max} \\
 & x[t + \Delta t] = A_d x[t] + B_d u[t] \\
 & y[t] = C_d x[t]
 \end{aligned} \tag{3}$$

MPC is widely considered simple to implement while offering sufficient performance and has been applied to various fields. Steps to implementation only requires (a) discretized model (b) objective function (c) selection of bounds (d) selection of parameters. The principal behind the basic form of MPC is relatively simple to understand.

- 1) The controller gathers measurements from the controlled system.
- 2) The controller computes optimal control sequences for the receding horizon.
- 3) The controller applies the first control step of the optimal control sequence to the controlled system.
- 4) Steps 1 to 3 are repeated.

As shown, the basic operating principal behind MPC closely follows the proposed architecture. Unlike conventional controllers such as PID, MPC is easy to implement and has implicit robustness—given the model is sufficiently accurate.

B. PREPARATION OF INTERNAL MODEL

The MPC from earlier needs a state-space representation of Fig. 1 to function. First, an abstract representation of Fig. 1 is prepared as shown in Fig. 4. The model consists of two parts as seen from the disturbance side: plant and controller. The power system block treated as a plant; the hydro and thermal response are both treated as a controller; and disturbance and EV support combined into one disturbance.

Using the abstract model, the sensitivity function between power system frequency (y) due to a combined change in disturbance and EV support (D) is,

$$\frac{P}{1 + PC} \tag{4}$$

By removing the hydro reserve and thermal reserve, both of which are saturation blocks, the overall sensitivity function

takes the following form,

$$\frac{\sum_{i=1}^{10} b_i s^i}{\sum_{j=1}^{11} a_j s^j}, \quad (5)$$

where b_i and a_j are coefficients. Since the model is too complex to practically utilize, this research reduced the model to a 3rd order model using Hankel Singular Value. Fig. 6 shows one example of a Hankel Singular Value for reduction—though, any reduction method should be sufficient.

With a 3rd order model, the transfer function reduces to the form,

$$\frac{\sum_{i=1}^2 b_i s^i}{\sum_{j=1}^3 a_j s^j}, \quad (6)$$

which is easily convertible to state-space form. Hence, the state-space representation of the internal model is,

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du. \end{aligned} \quad (7)$$

Discretizing the model with a zero-order hold approximation, the discrete-time state space form then becomes,

$$\begin{aligned} x[t + \Delta t] &= (I + A\Delta t)x[t] + (B\Delta t) \\ &= A_d x[t] + B_d u[t] \\ y[t] &= C_d x[t], \end{aligned} \quad (8)$$

where I indicate an identity matrix.

Furthermore, as outlined in Fig. 4, the formulated model combines disturbance and EV support as one input signal. Therefore, this model defines u as,

$$u = d + u^{ev}, \quad (9)$$

where d indicates the disturbance. Hence, indicating that the solution to the MPC will always have an offset with respect to the desired signal. Internal processing removes this offset.

C. SELECTION OF BOUNDS

The following two equations set the lower and upper bounds of the MPC:

$$u^{min} = P_{char} - P_{char}^{max} + d, \quad (10)$$

$$u^{max} = P_{char}^{min} - P_{char} + d, \quad (11)$$

where P_{char} indicates the base charge rate of all EVs, P_{char}^{max} indicates the maximum charging rate of all EVs combined, and P_{char}^{min} indicates the minimum charging rate of all EVs combined. The base charging rate P_{char} from above is,

$$P_{char} = N_{ev} (SoC^{max} - SoC_0) \frac{3600}{S_{base} \eta_c t_c}, \quad (12)$$

where N_{ev} is the total number of vehicles, SoC^{max} is the maximum State-of-Charge of one vehicle, SoC_0 is the initial SoC, S_{base} is the system base, η_c is the charging efficiency, and t_c is the time necessary for charge completion.

TABLE 1. List of unchanged parameters.

Parameter	Value
N	81
r	5
P_{char}^{max} per 1000 EVs (p.u)	5.821E-04
P_{char}^{min} per 1000 EVs (p.u)	-5.821E-04
$t(s)$	36000
SoC^{max} (MWh)	0.03
SoC^0 (MWh)	0.015
$f_{sips}(p.u)$	0.1
$d_{sips}(p.u)$	0.01
η_c	.88
T_{ev} (ms)	2000
P_{char} per 1000 EVs (p.u)	1.1642e-03
S_{base} (MVA)	33996
K_{prop} (FOPID)	-1.8903
K_{int} (FOPID)	-0.5577
K_{deriv} (FOPID)	-2.7021
λ (FOPID)	-0.7094
μ (FOPID)	0.9747

TABLE 2. List of sweep parameters.

Parameter	Values
Number of EV Groups (C)	1, 5, 10
Total EVs (N_{ev})	200k, 400k, 600k
Disturbance size (p.u) for step response	-0.05, -0.10
Disturbance time (s)	10.01, 11, 12
Load variation	As shown in Fig. 8
Data loss rate for load variation test (%)	0, 25, 50

D. SYSTEM INTEGRITY PROTECTION SCHEME

To overcome the potential drawback of having more control groups, the central controller incorporates SIPS characteristics. Since requiring a separate communication pathway dedicated for fast response makes deployment overly complicated, this research incorporates SIPS into the central controller by altering the upper bounds of the MPC under a certain condition. Fig. 6 graphically overviews the approach.

1) ACTIVATION CONDITION FOR SIPS

Like most protection schemes, SIPS must remain silent unless the system detects an emergency. Two metrics determine an emergency condition,

$$\begin{aligned} f &\leq f_{sips} \\ d &\leq d_{sips}, \end{aligned} \quad (13)$$

where f_{sips} and d_{sips} are thresholds for frequency and disturbance magnitude. Recovery from this critical condition will automatically make SIPS silent, prompting a normal operation of MPC.

2) SIPS CONTROL EFFECT

When SIPS is enabled, signaling an emergency, the central controller alters the MPC bounds. Assuming adjustment of charging rates to zero during an emergency is allowable in power system operation, the central controller adjusts the upper bounds of the MPC as follows:

$$u^{max, sips} = P_{char} + d \quad (14)$$

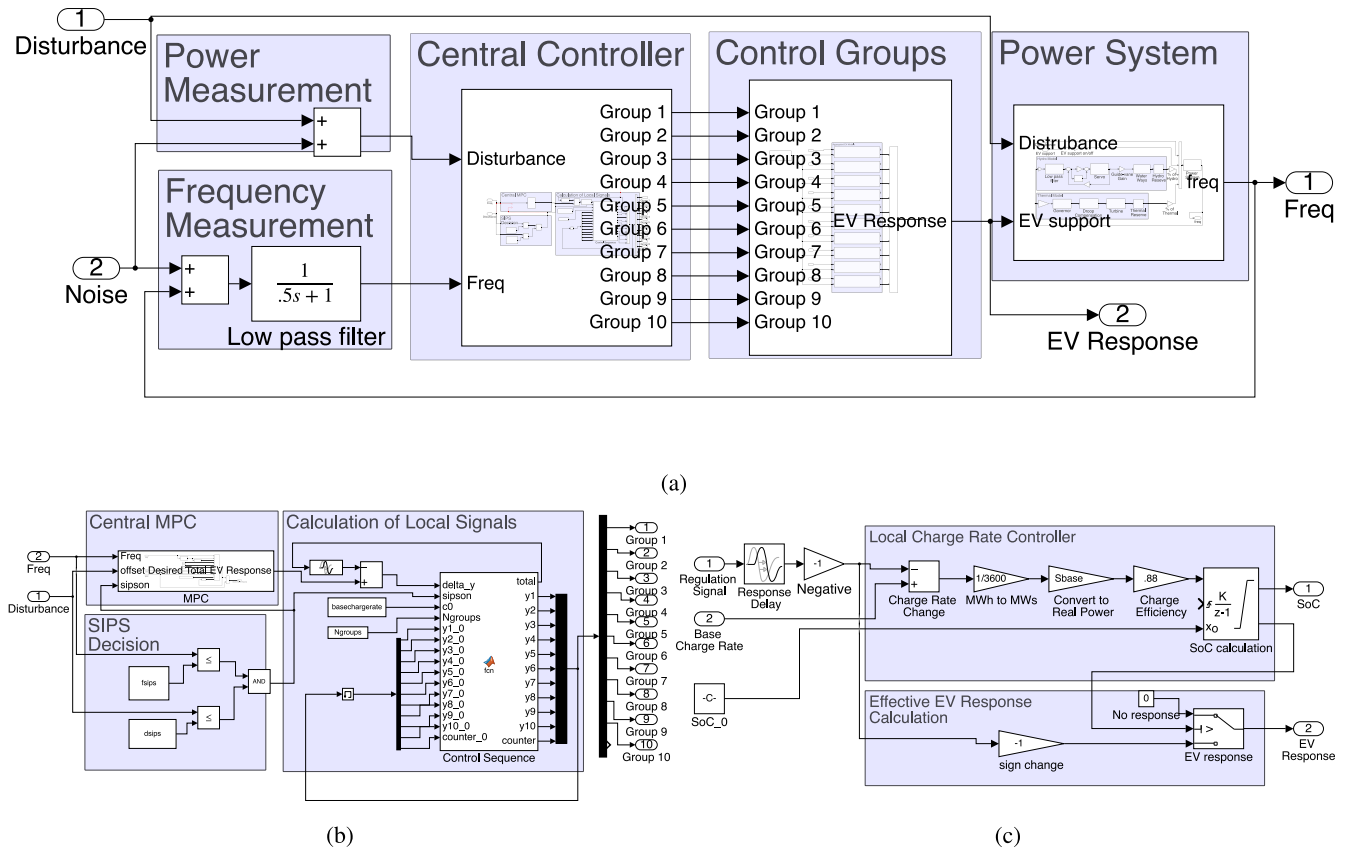


FIGURE 7. Simulink models. (a) Overall setup (b) Central controller (c) Aggregate EV within control groups.

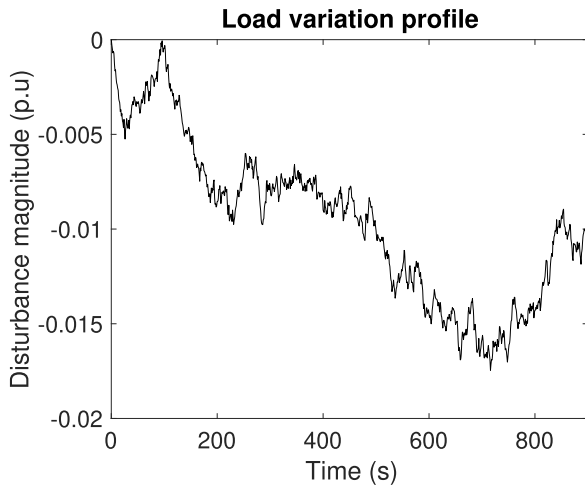


FIGURE 8. Load variation.

V. EVALUATION

A. EVALUATION METHODOLOGY

This research utilized the following metrics to evaluate the validity of the architecture:

- 1) If the proposed controller is beneficial in comparison to known controller.

- 2) If the asynchronous approach of the architecture show improvement over a synchronous approach.

Comparing the relative performance of the designed controller against a known controller evaluates the first metric. The evaluation chose FOPID controller from [23] as a comparison as it has been reported to be better performing than PID controllers—this is intuitive as PID controllers are a subset of FOPID controllers when integral and derivative terms are integer order. Comparing the relative performance of more control groups ($C > 1$) to a single control group ($C = 1$) evaluates the second metric.

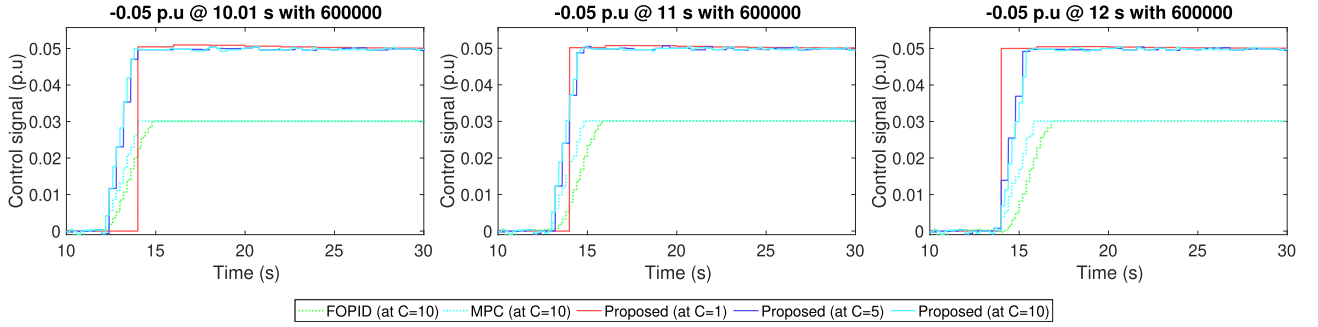
The evaluation used the Simulink model shown in Fig.7. The following briefly details the model:

- Power measurements, assumed to be from PMUs, measure the disturbance magnitude.
- Frequency measurement contains a low-pass filter to simulate the PMU frequency measurements.
- The central controller contains the SIPS decision logic, MPC logic, and calculation of control signals.
- The aggregate EVs within control groups responds to the control signal after a delay time of T_{ev} .

Parameters related to this study are adapted from area 1 of [37] and supplemented by parameters shown in Table 1. Specifically, this study selected T_{ev} based on the results

TABLE 3. Summary of improvements between proposed and FOPID at $C = 10$ for each type of test.

		Metric		
		Overshoot	Nadir	Settling
Step disturbance test	Average Improvement [%]	No improvement	21.77	41.67
	Min Improvement [%]	No improvement	6.46	6.84
	Max Improvement [%]	No improvement	36.35	100.00
Load variation test		σ	Min	Max
	Average Improvement [%]	36.27	44.69	65.38
	Min Improvement [%]	33.74	41.48	62.66
	Max Improvement [%]	38.85	47.38	71.20

**FIGURE 9.** Control signals for 600k vehicles and -0.05 p.u disturbance.

of [19]. Furthermore, this research utilized ICA, like [8], to determine parameters r and N of the central controller with code from [43].

Using this model, this evaluation conducts two types of tests: one for step disturbance (generation loss) and another for load variation. The step disturbance test verifies the effectiveness of the central controller and the effect of the SIPS decision on MPC (i.e., 1) from earlier). The load variation test aims to evaluate the performance of the proposed control architecture on varying signal loss conditions (i.e., the second metric from earlier).

For step disturbances, this evaluation chose disturbances sizes of -0.05 p.u and -0.10 p.u to consider two main scenarios. Disturbance of -0.05 p.u is approximately equivalent to a loss of wind farms ($500 \text{ MW} \times 3$) while a disturbance of -0.10 p.u is approximately equivalent to a loss of all renewable generation in a system with 10% renewable generation.

As for the load variation, this evaluation used the load profile across 900 seconds (15 minutes) shown in Fig. 8. The load variation emulates large renewable output variation. Furthermore, the evaluation used random control signal losses of 0%, 25%, and 50% to study the effects of control signal loss.

All tests use MPC without SIPS and FOPID tuned with ASO of [23] for comparison. The evaluation also used the fractional order tool kit of [44] after tuning with ASO from [45] to prepare the FOPID controller. Table 1 overviews the parameters relating to FOPID controller.

Although there are several parameters in the proposed architecture, this evaluation focused on the effect of varying the number of control groups (C). Table 2 lists all sweep parameters. This evaluation chose the number of controllable

EVs such that the number of EVs are less than the maximum possible based on the results of [37].

The evaluation is setup to be as fair as possible by utilizing the same architecture and interchanging the controller, keeping parameters consistent: each controller is tuned in accordance with the referenced research to keep consistently. However, it is important to note that it is expected that the proposed controller to perform better than other controllers in step disturbance tests as more EVs are instantaneous controlled. Hence, the step disturbance test only serves to verify that the SIPS scheme does not cause the controller to overshoot or fall into instability, rather than to simply compare the nadir.

B. EVALUATION RESULTS AND OBSERVATIONS

Table. 3 overviews the summary of improvements with respect to a FOPID controller at $C = 10$. Overall, the performance of the proposed architecture and controller, on average, had a 22.05% reduction in nadir in the step disturbance test and 36.27% reduction in standard deviation in the load variation test. The proceeding text covers the detail of each test.

1) STEP DISTURBANCES

Fig. 9 and Fig. 10 are control signals and frequency response for 600k vehicles and -0.05 p.u disturbance for varying disturbance timings. Before inspecting the overview of the results, these figures provide insight into the results.

Fig. 9 shows the example of control signals for 600k vehicles and -0.05 p.u disturbance for varying disturbance timings. Because the overall architecture is cyclic, there are vulnerable intervals in which the architecture cannot send the

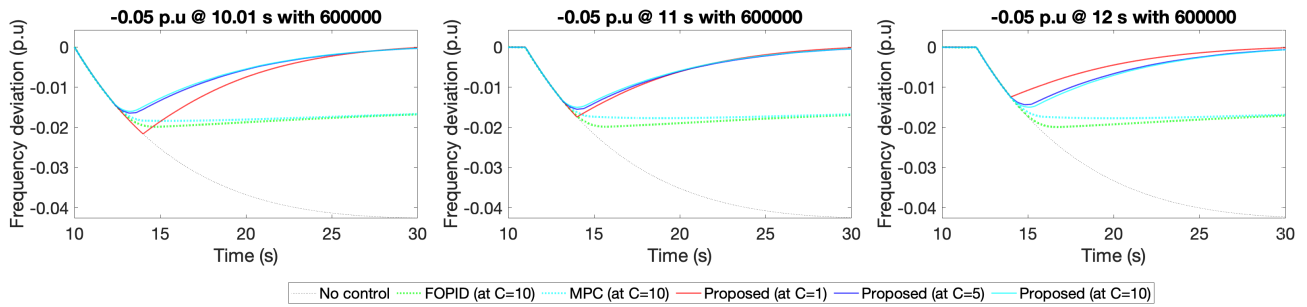


FIGURE 10. Relative performance between each setup for 600k vehicles and -0.05 p.u disturbance.

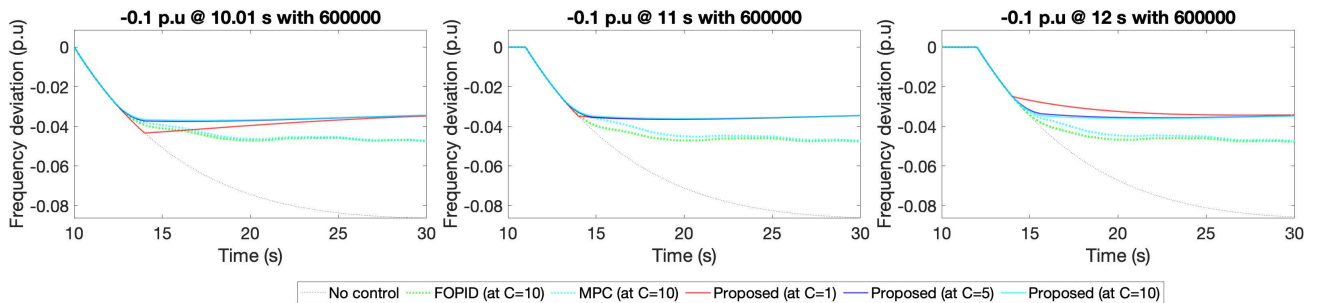


FIGURE 11. Relative performance between each setup for 600k vehicles and -0.1 p.u disturbance.

next control signal. The three different disturbance timings each highlight (a) directly after all control signals for all configurations (b) half a cycle after the control signal for $C = 1$ and (c) directly at the control signals. When comparing the three, the disturbance timing has minor impact on the control signals, unless $C = 1$. At $C = 1$, the difference in disturbance timing does play a significant role in delay timing variability which can vary between 0 to 2 seconds. This is verified in Fig. 10 where $C = 1$ responds the best when the disturbance timing is set to $t = 12.0$ (s). For a simple step disturbance, a faster response generally equated to better performance (a higher nadir).

When comparing the control signals between the FOPID, MPC, and proposed, each at $C = 10$, FOPID had the slowest response, followed by MPC, and proposed. This slower response also propagated to the frequency measurements of the system as shown in Fig. 10. The faster response and smaller deviation of the system was expected from this evaluation as more charge rates are terminated; however, this also comes at a cost of a minor variation of control signals in the post disturbance state. Although the variations are minor, the behavior does have a real-world implication of altering the charge rate of EVs. To what degree this may affect the EVs is unknown. At the very least, the inclusion of SIPS decision did not lead to an overshoot. Even without the SIPS decision, MPC performed better than FOPID, responding to events faster. This may be due to the ability of the MPC to determine

the present decision based on predicted future states unlike FOPID.

In Fig. 11, under a larger disturbance, the difference between the controllers and timing became minimal. Of course, the introduction of SIPS decision in the proposed controller does exhibit a higher settling frequency and nadir. Apart from $C = 1$, the nadir and settling frequency are converged to the same value. At this magnitude, the complete termination of charging cannot fully prevent a blackout, but only reduce it, as the frequency would deviate too much for this architecture to support.

Although the performance and characteristic of the proposed architecture under a step disturbance can be overviewed with these figures alone, a closer inspection of Table 4 reveal further insight.

Table 4 summarize the results for the step disturbance test. Table 4 shows the results in p.u deviation from the nominal frequency; therefore, multiplication with a respective nominal frequency of the power system would give a general intuition on the performance. For both FOPID and conventional MPC, the results show only the best configurations ($C = 10$). Overall, all cases showed improvement from the reference (no control), FOPID, and conventional MPC (i.e., no SIPS decision) regardless of the number of EVs or disturbance size. As with the earlier figures, these results meet expectations for this case due to the faster responding nature of the SIPS decision.

TABLE 4. Summary for disturbances.

Disturbance	EVs	Time	Metric	Ref.	FOPID (at C=10)	MPC (at C=10)	Prop.(at C=1)	Prop. (at C=5)	Prop. (at C=10)
-0.05	200k	10.01	Overshoot	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
			Nadir	-0.0426	-0.0340	-0.0340	-0.0257	-0.0255	-0.0254
			Settling	-0.0400	-0.0318	-0.0318	-0.0236	-0.0236	-0.0236
		11	Overshoot	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
			Nadir	-0.0426	-0.0340	-0.0339	-0.0254	-0.0254	-0.0254
			Settling	-0.0400	-0.0318	-0.0318	-0.0236	-0.0236	-0.0236
		12	Overshoot	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
			Nadir	-0.0426	-0.0340	-0.0339	-0.0252	-0.0253	-0.0254
			Settling	-0.0400	-0.0318	-0.0318	-0.0236	-0.0236	-0.0236
	400k	10.01	Overshoot	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
			Nadir	-0.0426	-0.0255	-0.0254	-0.0216	-0.0176	-0.0172
			Settling	-0.0400	-0.0236	-0.0236	-0.0071	-0.0071	-0.0071
		11	Overshoot	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
			Nadir	-0.0426	-0.0255	-0.0254	-0.0174	-0.0166	-0.0162
			Settling	-0.0400	-0.0236	-0.0236	-0.0071	-0.0071	-0.0071
		12	Overshoot	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
			Nadir	-0.0426	-0.0255	-0.0254	-0.0125	-0.0156	-0.0162
			Settling	-0.0400	-0.0236	-0.0236	-0.0071	-0.0071	-0.0071
	600k	10.01	Overshoot	0.0000	0.0000	0.0000	0.0007	0.0006	0.0005
			Nadir	-0.0426	-0.0199	-0.0184	-0.0216	-0.0165	-0.0160
			Settling	-0.0400	-0.0153	-0.0153	0.0002	0.0000	0.0000
		11	Overshoot	0.0000	0.0000	0.0000	0.0005	0.0004	0.0004
			Nadir	-0.0426	-0.0198	-0.0177	-0.0174	-0.0155	-0.0150
			Settling	-0.0400	-0.0153	-0.0153	0.0001	0.0000	0.0000
-0.1	200k	10.01	Overshoot	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
			Nadir	-0.0863	-0.0737	-0.0737	-0.0691	-0.0690	-0.0690
			Settling	-0.0810	-0.0693	-0.0693	-0.0645	-0.0646	-0.0646
		11	Overshoot	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
			Nadir	-0.0863	-0.0738	-0.0737	-0.0689	-0.0689	-0.0689
			Settling	-0.0810	-0.0693	-0.0693	-0.0646	-0.0646	-0.0646
		12	Overshoot	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
			Nadir	-0.0863	-0.0738	-0.0737	-0.0689	-0.0689	-0.0689
			Settling	-0.0810	-0.0693	-0.0693	-0.0646	-0.0646	-0.0646
	400k	10.01	Overshoot	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
			Nadir	-0.0863	-0.0611	-0.0611	-0.0524	-0.0519	-0.0518
			Settling	-0.0810	-0.0576	-0.0576	-0.0481	-0.0481	-0.0481
		11	Overshoot	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
			Nadir	-0.0863	-0.0613	-0.0612	-0.0518	-0.0518	-0.0517
			Settling	-0.0810	-0.0576	-0.0576	-0.0481	-0.0481	-0.0481
		12	Overshoot	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
			Nadir	-0.0863	-0.0614	-0.0613	-0.0514	-0.0517	-0.0517
			Settling	-0.0810	-0.0576	-0.0576	-0.0481	-0.0481	-0.0481
	600k	10.01	Overshoot	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
			Nadir	-0.0863	-0.0486	-0.0485	-0.0434	-0.0375	-0.0370
			Settling	-0.0810	-0.0459	-0.0459	-0.0317	-0.0317	-0.0317
		11	Overshoot	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
			Nadir	-0.0863	-0.0488	-0.0486	-0.0364	-0.0364	-0.0361
			Settling	-0.0810	-0.0459	-0.0459	-0.0317	-0.0317	-0.0317
		12	Overshoot	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
			Nadir	-0.0863	-0.0490	-0.0488	-0.0343	-0.0357	-0.0361
			Settling	-0.0810	-0.0459	-0.0459	-0.0317	-0.0317	-0.0317

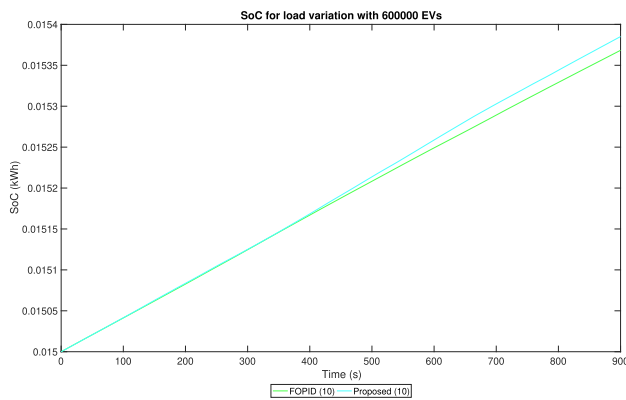
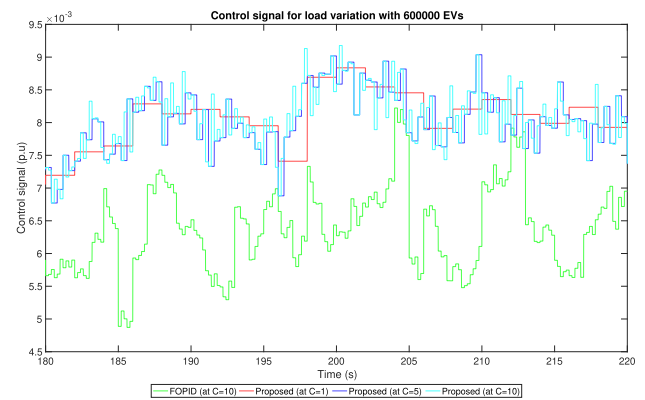
Upon closer inspection of Table 4, from the overshoot parameter alone, the performance of the proposed architecture and control scheme does little harm to the power system. This may be result of the modeling error inside the proposed MPC, where the reduction in order may have been one cause. Given the worst overshoot is 0.0007 p.u (+0.035 Hz in 50 Hz power system) at $C = 1$, $N_{ev} = 600k$, and $t = 10.01$ (s), delay time of the control signal may also be causing the overshoot. Because of the predictive property of MPC, the best cases exhibited no overshoot. Meanwhile, settling frequency

of the proposed improved from the reference and conventional MPC, but the results showed no differences between the configurations.

The frequency nadir, which is the most crucial factor in assessing the performance, improved with more EVs. Interestingly, the disturbance timing played a significant role in the nadir. $C = 1$ showed the best performance when the disturbance timing was at $t = 12$ (s). As the controller applies a larger control signal u under large disturbances, the results are within expectation. For disturbance timings

TABLE 5. Test results for load variation.

Loss[%]	EVs	Metric	Ref.	FOPID (at C=10)	Prop. (at C=1)	Prop. (at C=5)	Prop. (at C=10)
0	200k	σ	0.0033	0.0005	0.0002	0.0002	0.0002
		Max	-0.0000	0.0008	0.0007	0.0004	0.0004
		Min	-0.0129	-0.0018	-0.0006	-0.0006	-0.0006
	400k	σ	0.0033	0.0005	0.0002	0.0002	0.0002
		Max	-0.0000	0.0008	0.0007	0.0005	0.0004
		Min	-0.0129	-0.0018	-0.0006	-0.0005	-0.0005
	600k	σ	0.0033	0.0005	0.0002	0.0002	0.0002
		Max	-0.0000	0.0008	0.0007	0.0005	0.0005
		Min	-0.0129	-0.0018	-0.0006	-0.0005	-0.0005
25	200k	σ	0.0033	0.0005	0.0003	0.0002	0.0002
		Max	-0.0000	0.0008	0.0009	0.0005	0.0004
		Min	-0.0129	-0.0018	-0.0007	-0.0006	-0.0007
	400k	σ	0.0033	0.0005	0.0003	0.0002	0.0002
		Max	-0.0000	0.0008	0.0009	0.0005	0.0004
		Min	-0.0129	-0.0018	-0.0007	-0.0006	-0.0007
	600k	σ	0.0033	0.0005	0.0003	0.0002	0.0002
		Max	-0.0000	0.0008	0.0009	0.0005	0.0004
		Min	-0.0129	-0.0018	-0.0007	-0.0006	-0.0007
50	200k	σ	0.0033	0.0005	0.0004	0.0002	0.0002
		Max	-0.0000	0.0008	0.0012	0.0005	0.0004
		Min	-0.0129	-0.0019	-0.0014	-0.0006	-0.0007
	400k	σ	0.0033	0.0005	0.0004	0.0002	0.0002
		Max	-0.0000	0.0008	0.0012	0.0005	0.0005
		Min	-0.0129	-0.0018	-0.0014	-0.0006	-0.0007
	600k	σ	0.0033	0.0005	0.0004	0.0002	0.0002
		Max	-0.0000	0.0008	0.0012	0.0005	0.0005
		Min	-0.0129	-0.0018	-0.0014	-0.0006	-0.0007

**FIGURE 12.** State of charge for one vehicle in group 1 in the 600k vehicles and load variation test case. The proposed had a higher state of charge at the end of the evaluation.**FIGURE 13.** Control signals for 600k vehicles and load variation.

of $t = 10.01$ (s) and $t = 11$ (s), $C = 10$ had the best performance while $C = 5$ had a comparable performance—meanwhile, $C = 1$ showed reduced performance for these cases. Fig. 10 and Fig. 11 exemplify these cases where nadir is different between disturbance timings.

This may be one trade-off with including SIPS into the MPC. If the controller limits the control of EVs to emergencies only, “timing” of the disturbance should not matter; however, since the MPC is constantly active in the proposed architecture, the control interval directly determined by C has a crucial role. Considering the nadir differs significantly between C at $N_{ev} = 600k$ and $t = 10.01$ (s) in both disturbance sizes, having a considerable number of C may be crucial. Furthermore, the difference between the worst performing case and the best performing case is more apparent as the disturbance size increased. This is due to

rate-of-change-of-frequency (RoCoF) becoming steeper for larger disturbances: the delay time between the disturbance and EV response negatively affecting the outcome.

2) LOAD VARIATION

Table 5 shows the results for load variation test. For FOPID, the results show only the best configuration ($C = 10$). Furthermore, Fig.13 shows an example of the control signals. Overall, the proposed architecture performed well, regardless of the controller used. Albeit the relative performance increase FOPID exhibited from the reference, the designed MPC performed better even with smaller number of control groups. Performance difference became noticeable as random signal losses increased. An added observation is the difference in SoC at the end of the evaluation period. Fig. 13 shows an example of this behavior, where a slightly higher SoC levels are observed for the proposed controller. Although the

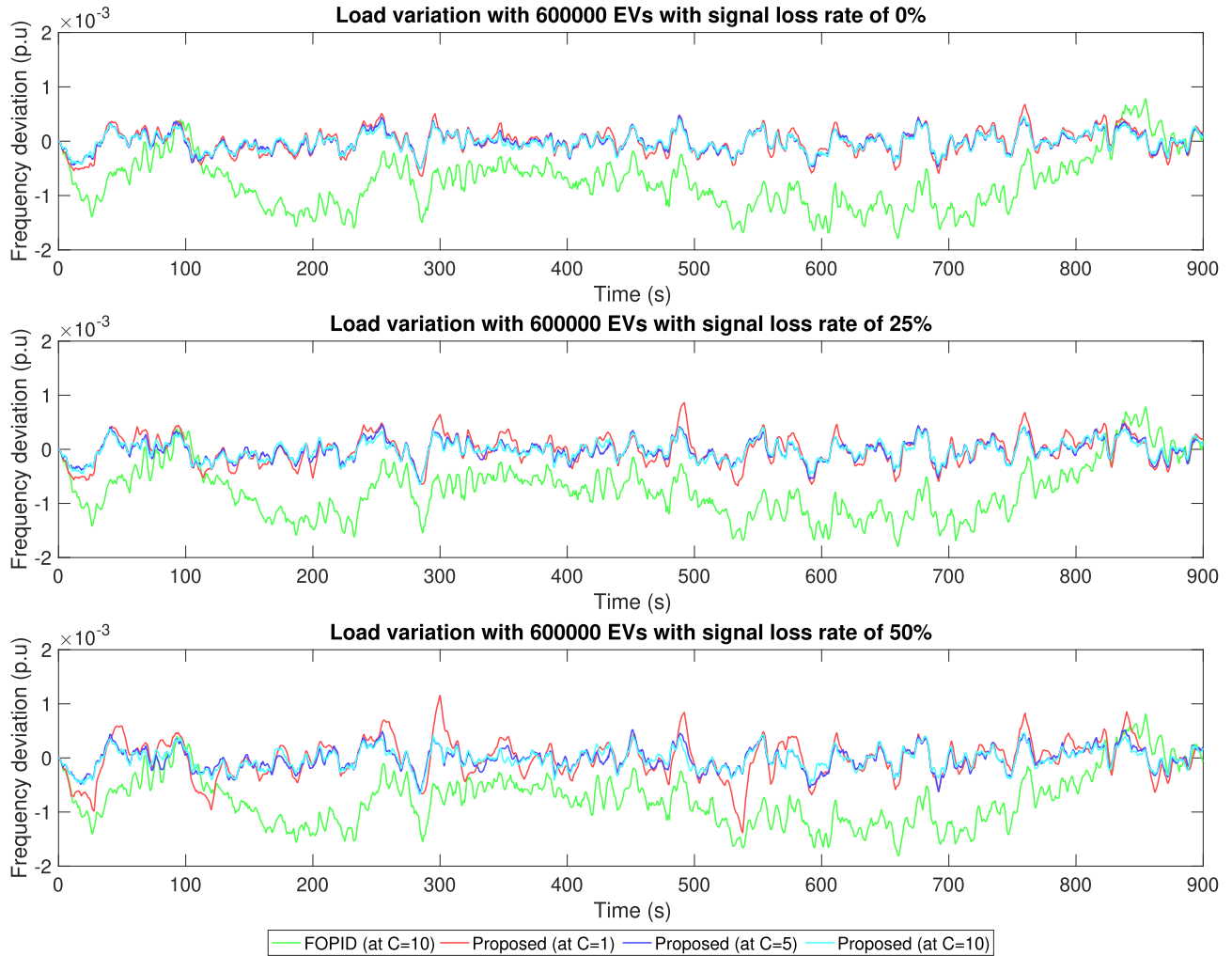


FIGURE 14. Frequency during the 15 min period for varying signal loss rates.

difference is insignificant, this may be an added benefit of MPC, where the total amount of control is headed towards minimization

When focusing on cases with no signal loss for the proposed, $C = 5$ and $C = 10$, showed the best performance in all the cases; however, the standard deviation did not differ between the number of control groups nor the number of EVs. The only notable difference is in the maximum and minimum, where $C = 1$ performed slightly worse than $C = 5$ and $C = 10$. For cases with signal losses, the difference is more evident. The evaluation observed higher performance with higher C as visualized in Fig. 14.

One explanation for this behavior may be an inherent property of MPC, where the next control sequence utilizes the previous control signal. If the communication pathway loses the control signal, MPC will take this into consideration for the next control signal and correct the trajectory. This property of MPC, which has an implicit robustness, plays in favor with the proposed control architecture.

3) ASSESSMENT OF THE EVALUATION

Overall, the proposed frequency control architecture performed well in comparison to the reference, MPC without SIPS, and FOPID controller. Incorporation of SIPS into the MPC of the central controller allowed for effective control of power system frequency in both step disturbances and load variation. When using the proposed architecture, having more than 1 control group yielded better results for step disturbances and load variation; however, the benefits were more significant on load variation, especially with signal losses considered.

VI. CONCLUSION

A. LIMITATION OF THE RESEARCH

The contribution as presented in the research addresses one practical approach to field deploying frequency control with EVs. Based on the evaluation, the proposed control scheme is viable, showing sufficient performance on major test cases. The relatively simple nature of the scheme is easy to understand, engineer, and deploy in comparison to a more complex

control scheme and controller—the main challenge was to keep the overall scheme relatively simple, while ensuring a significant performance increase. For instance, the alternative architecture combined with other types of controllers, such as sliding mode controllers, may offer superior performance, but the design of the controller would be much more complex.

Despite the benefits provided, the proposed architecture has several limitations: these can be divided into the limitation of the architecture and limitation of the controller. The first limitation is the lack of resilience against a failure of the central controller. Although the current scheme is resilient against signal losses to the local controllers, this is not true about the central controller. Further consideration is necessary to overcome this issue. Another limitation lies within controller itself. As MPC was selected with respect to the relative advantage over LQ and PID controllers for performance, the robustness cannot be explicitly guaranteed. Furthermore, other forms of robust controllers and adaptive controllers were not compared, hence, there may be other suitable controllers. Furthermore, as SoC management was not the main focus of this research, further research may be possible into this direction, by utilizing the MPC's property of defining hard constraints.

B. SUMMARY AND NEXT STEPS

This research proposed a frequency control architecture of electric vehicles which utilizes Open Charge Point Protocol characterized by an asynchronous use of control groups. The proposed architecture provides frequency regulation through adjusting the charge limit of electric vehicles in each control group. Furthermore, to effectively utilize the proposed architecture, the designed model predictive controller incorporates a system integrity protection scheme behavior. Through an evaluation on an aggregated power system model, the proposed architecture performed sufficiently for both large step-disturbances and load variations regardless of the number of electric vehicle groups present. All tests observed better results when more electric vehicle control groups were allocated in the architecture. In comparison to a tuned fractional-order proportional integral derivative controller, the proposed architecture and controller, on average, had a 21.77% reduction in nadir in the step disturbance test and 36.27% reduction in standard deviation in the load variation test.

With promising evaluation results, opportunities for use in other applications of the power system such as steady-state voltage control or congestion management are now a possibility. Future work includes designing a different central controller for these specific purposes to expand the use case of the architecture.

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KENTA KIRIHARA (Member, IEEE) received the B.S. degree in electrical engineering and the M.S. degree in electrical and computer engineering from the University of Illinois at Urbana-Champaign, in 2013 and 2015, respectively, the Ph.D. degree in engineering from the Computer Science Program, University of Tsukuba, in 2022. He joined the Research and Development Division, Hitachi, in 2015, where he is currently a Senior Researcher. His current

research interest includes the use of optimization methodologies in the field of power and energy systems.



TOHRU KAWABE (Member, IEEE) received the B.Eng. degree in applied mathematics and physics, the M.Eng. degree in applied systems science and Dr.Eng. degree in applied mathematics and physics from Kyoto University, Japan, in 1988, 1990, and 1997, respectively. Since 2013, he has been a Full Professor with the Division of Information Engineering, Faculty of Engineering, Information and Systems, University of Tsukuba, Japan. His current research interests include biologically inspired technology and robust control.

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