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Research

DETERMINATION of STABILITY MARGINS in SINGLE AREA LOAD FREQUENCY CONTROL SYSTEM HAVING INCOMMENSURATE COMMUNICATION DELAYS DUE TO PLUG-IN ELECTRIC VEHICLES

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ABSTRACT

This work investigates the impact of time delays on the stability of a single-area load frequency control (LFC) system that includes plug-in multiple electric vehicles (EVs) aggregators to regulate the system frequency. Communication delays are caused by open communication networks used to transceive control signals. These delays can degrade the performance of the controller leading to undesired system frequency oscillations and may even cause instability if they exceed an upper bound limit known as stability margin. These delays can be commensurate or incommensurate depending upon the nature of the communication network. Hence, it is important to determine stability margins of the single-area LFC system with plug-in EVs aggregators to ensure the stable operation under both types of delays. This study determines the stability margins for extensive proportional-integral (PI) controller gains of the single-area LFC system with plug-in EVs by implementing a simulation approach. The knowledge of stability delay margins makes it possible to appropriately tune the PI controller gains that ensure a stable operation of the LFC system even in the presence of inevitable communication delays.

Keywords: Load frequency control, Electric vehicles, Communication delays, Stability margins

1. INTRODUCTION

Renewable energy (RE) resources have been highly regarded in the power generation due to increasing environmental concerns. However, such a power generation supplies variable electric power output and may cause irregularities in the desired system frequency. Although, Energy Storage System (ESS) of batteries can be utilized as an alternate to obtain constant power output, but, it is an expensive power source. Interestingly, EVs batteries can be used for large-scale energy storage in the power system. EVs have become perceptible in frequency regulation of independently controlled interconnected systems [1]. Their batteries can decrease or increase power output faster than traditional generation sources. This attribute of EVs enables the LFC system to improve its dynamic performance. EVs are capable of reducing fluctuations to improve frequency response because they can be utilized as generators and loads [2]-[3]. An entity known as aggregator is required by EVs to practically participate in frequency regulation market. The entity aggregates and controls a large fleet of EVs [4]-[7]. The prime objective of an aggregator is to transceive information regarding the status of EVs to/from LFC controller and rearrange the control command for dispersing EVs. Figure.1 shows a schematic of EVs plugged into the grid as a power source using vehicle-to-grid (V2G) technique.

EVs need some kind of communication network to transceive control signals to and from the LFC system controller. In general, open distributed network is used for this communication. But, such networks are susceptible to communication delays [6], [8]-[9]. These delays can result into an unstable LFC system in spite of an expectation that EVs are capable of improving the dynamic system performance. Thus, it is necessary to analyze delay-dependent system stability improved by EVs. Also, it is important to determine the stability margins which is defined as the admissible upper bound limit of the communication delay [8].

A number of approaches are discussed in the existing literature to identify the stability margins of dynamical systems experiencing communication delays. The approaches can be classified as: a) time-domain approaches and b) frequency-domain direct methods. The latter intends to compute complex roots of the characteristic polynomial of the system on the imaginary axis. This group is comprised of approaches like; removal of transcendental terms in the characteristic polynomial [10], the contour integral (or, argument principle) method [11], delay space re-scaling approach [12], Schur-Cohn method [13] and Rekasius

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substitution [14] - [15]. This group of methods is able to calculate exact stability margins. But, the basic shortcoming of these approaches is that they cannot compute delay margins for the case of time-varying communication delays.

A comprehensive literature review on the stability margin estimation methods for linear continuous time-invariant systems experiencing constant communication delays is presented in [16]. Among those approaches, the direct method depending upon the elimination of transcendental terms [10] is effectively implemented in [17] to identify stability margins for time-delayed LFC systems. The Rekasius substitution method is employed for computing stability margins for single-area LFC system with plug-in EVs aggregator [18]. The delay space re-scaling approach presented in [12] is employed for determining the stability margins of hybrid ESS having hierarchical DC micro-grids control and experiencing multiple communication delays. The latter group of methods uses linear matrix inequalities (LMIs) method together with Lyapunov stability theory. These methods are presented in [8], [19] to compute the stability margins of LFC systems and in [20] to calculate the stability margins of micro-grid. Both constant and time-varying delay problems can be addressed using this group of indirect methods, but, they provide more conservative stability margins when compared with the previously discussed group of direct methods [17].

This work is the extended version of the paper titled, *Stability Analysis of a Single-Area Load Frequency Control System with Electric Vehicles Group and Communication Time Delays* [21]. The reported work presented only the effect of commensurate delays on LFC system with plug-in EVs. However, this work implements time-domain simulations [22] based approach for determining stability margins in single-area LFC system with multiple plug-in EVs aggregators while considering both commensurate and incommensurate delay scenarios. Since, each EVs aggregator may have different communication delays depending upon the technical specifications of communication technologies and networks, it is more practical to compute stability margins for both commensurate and incommensurate communication delays. Consequently, the impact of EVs participation ratio on the stability margins and the changes in stability margins relating to controller gains is also examined. The use of this approach allows to obtain exact values of stability margins.

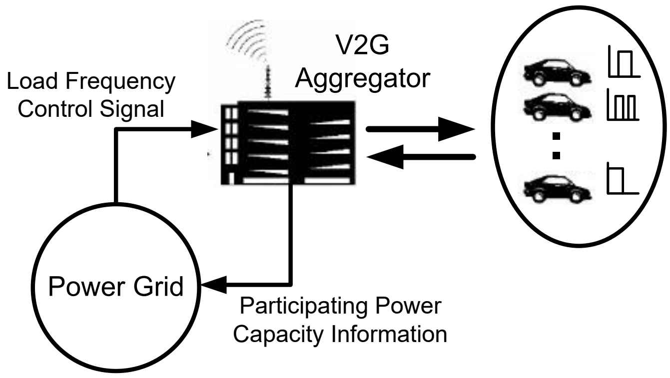

Figure 1. EVs participation in frequency regulation service.

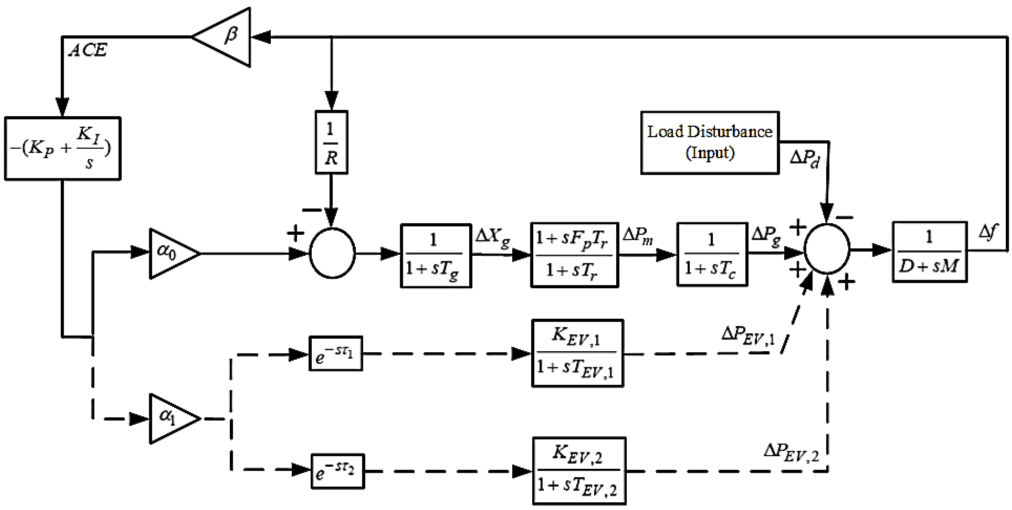

Figure 2. Dynamic model of single-area LFC system with EVs and communication delays.

2. TIME-DELAYED SINGLE AREA LFC SYSTEM DUE TO THE PARTICIPATION OF EVs

A single-area LFC system with two plug-in EVs aggregators is shown in Figure 2. The EVs batteries model is defined by a first-order transfer function as follows [8]:

$$G_{EV,i}(s) = \frac{K_{EV,i}}{1 + sT_{EV,i}} \tag{1}$$

where $T_{EV,i}$ and $K_{EV,i}$ denote the time constant and gain of the EVs battery system when $(i = 1,2)$.

In Figure 2, Δf and ΔP_d denote the frequency deviation and the load disturbance. Moreover, ΔP_g, ΔP_m, ΔX_g, ΔP_{EV1} and ΔP_{EV2} represent the generator power output, mechanical power output, the valve position and the power output of both the EVs aggregators, respectively. Furthermore, D, R, β, F_P, T_c, T_r, T_g and M denote the damping coefficient, speed regulation, frequency bias factor, fraction of the turbine power, time constants of the turbine, reheat, governor and inertia constant of generator, respectively. Whereas, K_P and K_I represent PI controller gains and the area control error is symbolized by ACE.

ACE is transmitted to PI controller as a control signal whenever there is any sudden change in the load demand. The PI controller sends the signal to EVs aggregators or reheat steam turbine depending on their participation ratios α_1 and α_0 to regulate the system frequency. The control signal received by the EVs aggregators over some kind of communication network allows them to participate in frequency regulation. It should be noticed that the communication delays from LFC controller to the first EVs aggregator (τ_1) and from LFC controller to the second EVs aggregator (τ_2) are considered as commensurate (integral multiple of each other or equal to each other) in the first scenario and incommensurate in the other scenario. These communication delays are modelled by the exponential functions of $e^{-s\tau_1}$ and $e^{-s\tau_2}$ in Figure 2. It should be emphasized here that the incommensurate delay case is the most realistic one since EVs aggregators might have different communication infrastructures that result in incommensurate (not integer multiple of each other) communication time delays [8].

It is to be mentioned here that due to the self-deployment of communication links by the Independent System Operator (ISO) and the open communication links used between EVs aggregator and EVs, only communication delays from EVs aggregators to EVs are considered in this study as the delays observed in the transmission of regulation signal from ISO to the conventional generation are less significant [23], [24].

3. IDENTIFICATION OF STABILITY MARGINS

The prime objective of stability analysis is to investigate the delay-dependent or delay-independent stability of time-delayed systems. The system will be stable for all the finite time delay values in delay-independent stability case. Whereas, in case of delay-dependent stability, the system will be stable when $\tau < \tau^*$ where τ and τ^* denote communication delay and stability margin, respectively. However, the system would be unstable as the delay values go beyond the stability margin $\tau > \tau^*$. The stability margin is the deciding factor in estimation of LFC system stability. The stability delay margin represents the maximum value of the time delay such that the LFC system will be at least marginally stable [17, 19]. For LFC system to be stable, the total communication time delay must be less than the stability delay margin. The information of stability margins for wide-ranging parameters is necessary to examine stability of the system.

Theoretically, all the roots of the characteristic polynomial of the single-area LFC system with plug-in EVs aggregators must be lying on left half of the $s-$plane to satisfy the required condition of asymptotic stability. Taking both the delays into account, the stability margin problem is all about finding value of τ^* for which the characteristic polynomial will have roots (if there exist any) on the $j\omega-$axis. Hence, time-domain simulations are executed for finding this boundary beyond which the system shows an unstable response.

4. SELECTION OF COMMUNICATION DELAYS

The communication delays τ_1 and τ_2 are expressed in polar coordinates $(|\tau|, \theta)$ as reported in [25]. All points are defined as $T(\tau_1, \tau_2)$ on a boundary relying on $(|\tau|, \theta)$ in $(\tau_1, \tau_2)-$space. Magnitude $|\tau|$ is defined as $|\tau| = \sqrt{\tau_1^2 + \tau_2^2}$ and angle θ as $\theta = \tan^{-1}(\tau_2/\tau_1)$. This polar coordinate representation of the communication delays enables us to examine the impact of commensurate communication delays on the stability margin by keeping the angle $\theta = 45^0$ fixed for the given values of magnitude $|\tau|$. However, any other θ value enables the user to investigate incommensurate communication delays like; $\theta = 60^0$ discussed in this study. $\theta = 60^0$ corresponds to the scenario when the communication delay between the LFC controller and second EVs aggregator is greater than the communication delay between the LFC controller and first EVs aggregator $(\tau_2 > \tau_1)$.

5. RESULTS AND DISCUSSIONS

Results of Stability margin computed by time-domain simulations for the single-area LFC system with plug-in EVs aggregators are presented in this section. For (*i*= 1, 2) the system parameters are given as [8]:

$$\begin{aligned} &D = 1,\ \mathrm{R} = 1/11,\ F_P = 1/6,\ \beta = 21,\ M = 8.8,\ T_g = 0.2\ s, \\ &T_c = 0.3\ s,\ T_r = 12\ s,\ T_{EV,i} = 0.1\ s,\ K_{EV,i} = 1 \end{aligned} \tag{2}$$

5.1. Commensurate Communication Delays

The selection of multiple delays (τ_1, τ_2) is done by using the polar coordinates and specifying the values of (τ_1, τ_2) by choosing $|\tau^*|$ and θ. In order to analyze the effect of various commensurate delay values on stability margins, the angle is fixed at $\theta = 45^0$. It should be noticed that the angle $\theta = 45^0$ corresponds to the scenario in which the delay from both the EVs aggregators to the EVs is same $\tau_1 = \tau_2$. The values of the corresponding stability margin magnitude $|\tau^*|$ for this case are presented in Table 1. Whereas, the time-domain simulation results are shown in Figure. 3. It can be clearly observed from the dashed line in Figure 4 that the oscillations in the frequency response of LFC-EVs system damped out showing stable operation of the system for the given parameters of PI controller $(K_P = 0.6,\ K_I = 0.8)$ and the stability delay margin magnitude $|\tau| = 0.97\ \text{sec}$. However, sustained oscillations in the frequency response represented by solid line in Figure 3 show that the system is marginally stable for $(K_P = 0.6,\ K_I = 0.8)$ and $|\tau| = 0.9804\ \text{sec}$. Even a slight change beyond this stability margin value will make the system unstable. As shown by dotted line in Figure 3, the oscillations in the frequency response of LFC-EVs system are increasing for $(K_P = 0.6,\ K_I = 0.8)$ and $|\tau| = 0.99\ \text{sec}$ showing an unstable operation of the system.

Moreover, the stability margin reduces with an increment in K_I for all K_P values. However, the stability margin values at first increase and then start to decrease after a specific point with an increase in K_P when K_I is fixed. These variations in the stability delay margins against the PI controller gain values for $(\alpha_1 = 0.2)$ are shown in Figure 4.

It is also imperative to examine the impact of EVs participation in the LFC system. Figure 5 shows the variation in the stability margins when the participation of EVs aggregator gradually increases. For $(K_P = 0.6,\ K_I = 0.8)$, it can be observed that the stability margin values of the system show a smooth decrement while the participation factor of EVs increases from 10% to 50%.

Table 1. Stability margins for commensurate delays $(\tau_1 = \tau_2)$

$\lvert\tau^*\rvert$	K_I				
K_P	**0.2**	**0.4**	**0.6**	**0.8**	**1.0**
0.2	2.7840	1.1770	0.6511	0.3929	0.2416
0.4	3.1198	1.6890	1.0795	0.7463	0.5385
0.6	2.7470	1.8295	1.3081	**0.9804**	0.7582
0.8	2.2529	1.7302	1.3575	1.0875	0.8872
1.0	1.8377	1.5418	1.2962	1.0965	0.9354

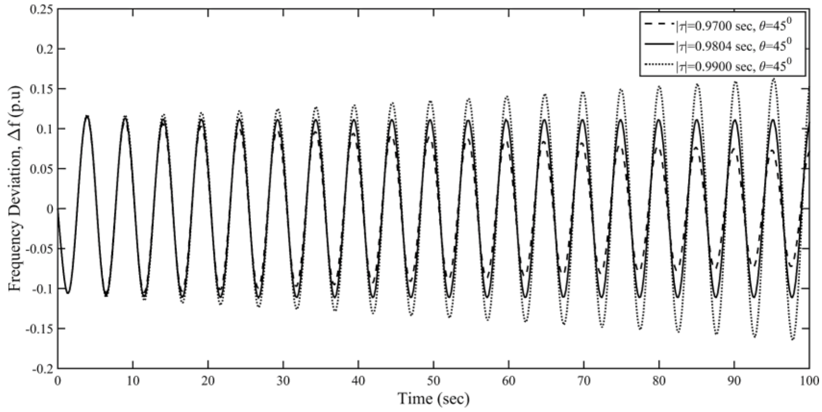

Figure 3. Frequency deviations for commensurate delays case when $(K_P = 0.6,\ K_I = 0.8)$.

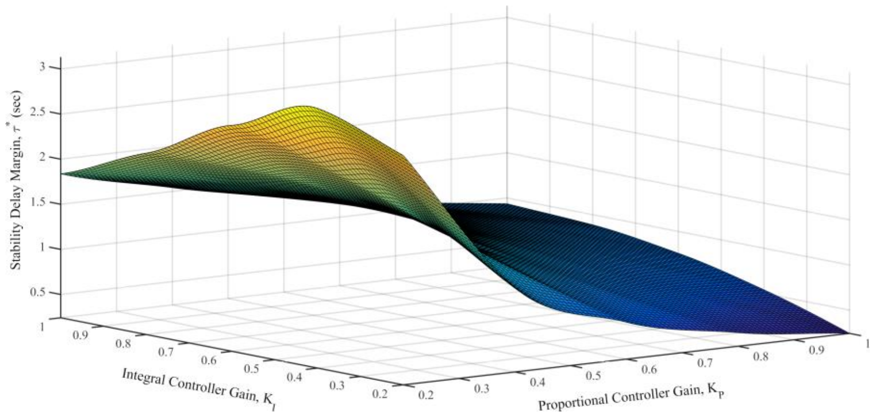

Figure 4. Variation of stability margins with respect to controller gains for $\theta = 60^0$.

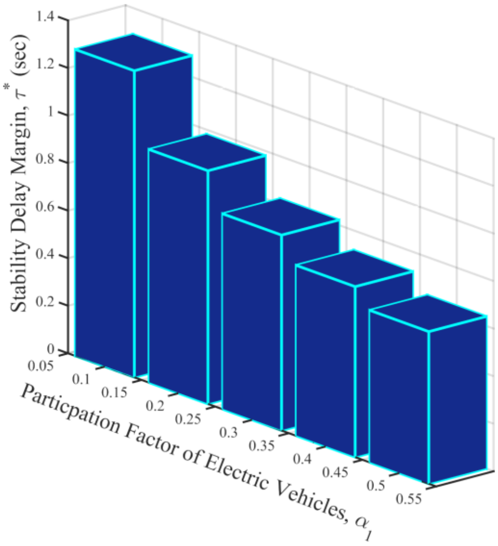

Figure 5. Variation of stability margins with respect to participation of EVs for $\theta = 45^0$.

5.2. Incommensurate communication delays

The impact of different incommensurate delay values (τ_1, τ_2) on stability margins is investigated by fixing the angle at $\theta = 60^0$. This corresponds to the scenario when $(\tau_2 \neq \tau_1)$. The values of the corresponding stability delay margin magnitude $|\tau|$ for this case are presented in Table 2 and the time-domain simulation results are shown in Figure 6. For a given set of PI controller gains $(K_P = 0.6,\ K_I = 0.6)$ and the stability margin magnitude $|\tau| = 1.35$ sec, the dashed line illustrates that oscillations in the frequency response of LFC system with plug-in EVs aggregators damped out showing stable operation of the system. However, sustained oscillations in the frequency response represented by solid line show that the system is marginally stable for $(K_P = 0.6,\ K_I = 0.6)$ when $|\tau| = 1.3833$ sec. Likewise, a slight change beyond this stability margin value will make the system unstable. As shown by the dotted line in Figure 6, the oscillations in the frequency response of LFC-EVs system are increasing for $(K_P = 0.6,\ K_I = 0.6)$ when $|\tau| = 1.40$ sec.

Similar to the commensurate delays scenario, the stability margin decreases with an increase in K_I for all values of K_I. Also, these values show a same trend by initially increasing and then decreasing after a specific point with an increase in K_P when K_I is fixed. These variations in the stability delay margins against the PI controller gain values for $(\alpha_1 = 0.2)$ are shown in Figure 7.

The impact of the participation of EVs in the LFC system is also studied for commensurate delays case. Figure 8 shows the variation in the stability margins when the participation of EVs gradually increases. For $(K_P = 0.6,\ K_I = 0.6)$, it can be observed that the delay margin values of the system show a sudden initial decrease and keeps on decreasing when the participation factor of EVs increases.

Table 2. Stability margins for incommensurate delays $(\tau_1 \neq \tau_2)$

$\lvert\tau^*\rvert$	K_I				
K_P	**0.2**	**0.4**	**0.6**	**0.8**	**1.0**
0.2	2.9954	1.2274	0.6751	0.4068	0.2504
0.4	3.5050	1.7890	1.1285	0.7761	0.5592
0.6	3.1845	1.9775	**1.3833**	1.0266	0.7898
0.8	2.6490	1.9089	1.4562	1.1505	0.9315
1.0	2.1595	1.7244	1.4092	1.1733	0.9900

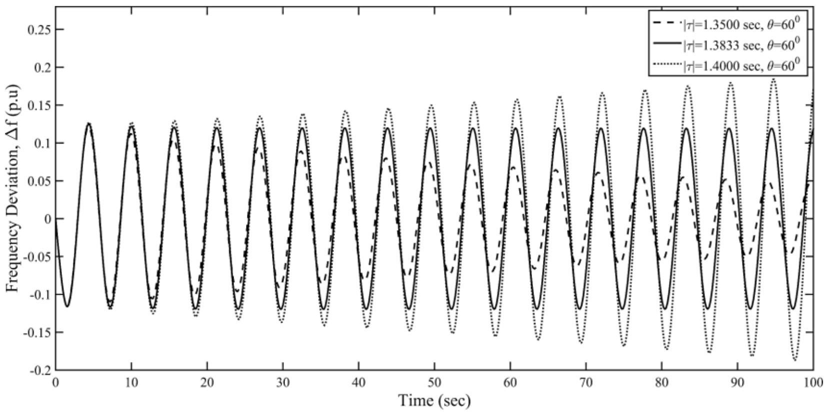

Figure 6. Frequency deviations for incommensurate delays case when $(K_P = 0.6,\ K_I = 0.6)$.

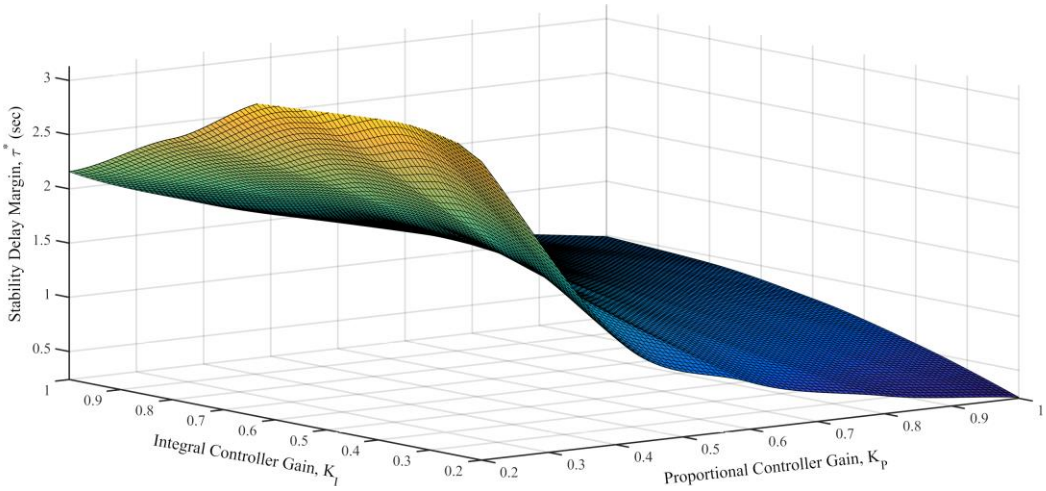

Figure 7. Variation of stability margins with respect to controller gains for $\theta = 60^0$.

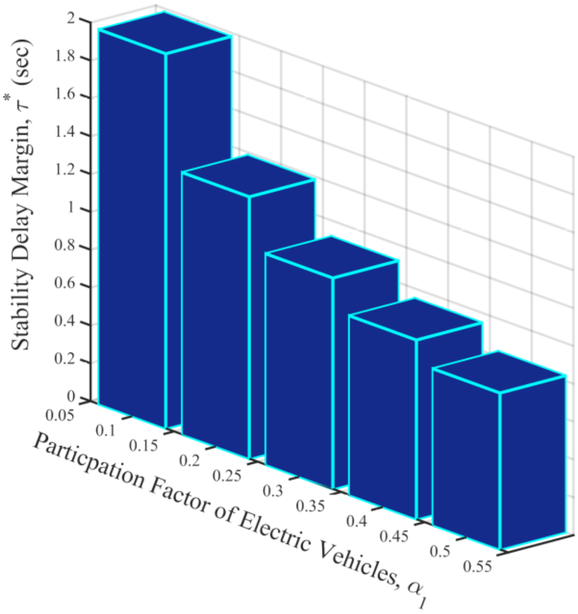

Figure 8. Variation of stability margins with respect to participation of EVs for $\theta = 60^0$.

6. CONCLUSION

A simulation based approach is presented in this work to identify stability margins over an extensive range of PI controller gains in the single-area LFC system with plug-in EVs and multiple communication delays. The technique is effectively implemented for both commensurate and incommensurate time delays. It is observed that communication delays arise due to the integration of EVs into the LFC system that leads to the destabilization of the system when the delay value exceeds the stability margin. It can be seen from the table that for a fixed K_P value, stability margin is decreasing with an increase in K_I values. Also, the delay margins initially increase and then start to decrease with an increase in K_P value when K_I is fixed. Moreover, the stability margin decrease when the participation of EVs increases. For future studies, this delay dependent stability analysis would be extended to multi-area LFC-EVs system considering uncertainties in the system parameters.

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