

Impact of PLL on Harmonic Stability of Renewable Dominated Power System: Modeling and Analysis

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Abstract—For reliable operation of power system, the system should be stable not only in the fundamental domain but also in harmonic domain. Power electronic converters of renewable generators inject harmonics into the power systems. So, at higher renewable penetration levels, study of power system stability in harmonic domain i.e. harmonic stability is required. The Phase Locked Loop(PLL) is used for grid synchronization of renewable generators. PLL affects the dynamic behavior of power electronic converters in harmonic domain also. This paper analyzes the impact of PLL on the harmonic stability of renewable dominated power systems. A small signal state space model is developed for PLL in harmonic domain to analyze the behavior of PLL. The obtained state space model is a periodic Linear Time Varying (PLTV) system, making the state space model of the whole power systems also a PLTV system. As the obtained state matrix is periodic in nature, the concept of time varying eigen-values is employed to analyze the harmonic stability. The standard IEEE-39 bus system is modified to enable high renewable penetration level and the modified system is used to carryout the harmonic stability analysis. Impact of PLL parameters on harmonic stability is analyzed using the modified IEEE 39 Bus system. The impact of renewable penetration level on harmonic stability for given PLL parameters is also analyzed. It is observed that the PLL parameters and renewable penetration level have impact on the harmonic stability of power system.

Index Terms—Phase Locked Loop, Renewable Integration, Harmonic Stability.

I. INTRODUCTION

Power systems are experiencing a major shift in power generation paradigm in the interest of impact on the environment due to fossil fuel-based generation. In future, power system is expected to rely on Renewable Energy (RE) sources such as wind and solar. Power electronic converters are often used to interface these RE sources with the power grid for better control. This type of RE generators are referred to as Converter Control-Based Generators (CCBGs). Several studies have focused on understanding the impact of RE on power system [1]–[3].

For reliable operation of grid, stability of the power system is one of the main concerns. Conventional power system being dominated by Synchronous Generators (SGs), stability of the system is analyzed only in the fundamental frequency domain. With increasing penetration of RE, CCBGs are going to play an important role in power system stability [4]–[6].

The harmonics injected by converters and their interaction with other components of power system may affect the stability of system in harmonic domain. In addition, the significant presence of power electronic interfaced loads in the system may affect the stability. The oscillatory stability challenges faced by power system due to the harmonic injections is referred to as harmonic stability [7]–[9]. Analyzing the harmonic stability and developing ways to mitigate the instability have drawn significant attention of research community.

Phase Locked Loop (PLL) is an integral component of CCBGs. PLL is known to have impact on the dynamics and stability of power system [10]–[13]. Impact of PLL dynamics on power system dynamics in fundamental frequency domain has been explored in the literature [10]–[13]. Reference [10] discusses the impact of PLL dynamics on power system small signal behavior of voltage source converter (VSC) in a high voltage DC transmission system. Reference [11] discusses the impact of PLL on electromechanical response of wind generator under transient conditions. The coupling between positive and negative sequence impedances due to PLL and its importance from the aspect of stability is discussed in [12]. The low frequency behavior and stability of PLL under different grid impedance scenarios is investigated in [13] using a non-linear model. However, there is not much work on the impact of PLL on the harmonic stability of renewable dominated power systems. This paper tries to fill this gap. This paper analyzes the impact of PLL on the harmonic stability of renewable dominated power systems. The main contributions of this paper are,

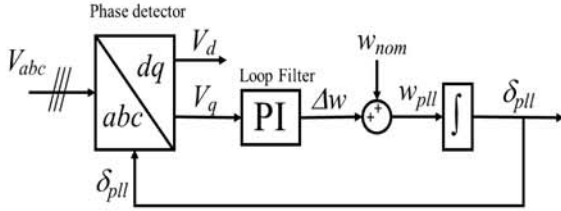
- Small signal state space model of Synchronous Reference Frame-PLL (SRF-PLL) is developed for harmonic-domain dynamic studies. However, the state space models for other type of PLLs can be developed by following the same procedure.
- Harmonic stability analysis of a power system with high RE penetration (VSC based).
- Impact of PLL parameters on harmonic stability.
- Impact of RE penetration level on harmonic stability for given PLL parameters.

It is observed that the PLL parameters and RE penetration level have impact on the harmonic stability of power system.

II. MODELING AND STABILITY ANALYSIS IN HARMONIC DOMAIN

A. Phase Locked Loop Model in Harmonic Domain

PLL is used for grid synchronization in CCBGs. The PLL estimates the phase angle of its input signal, usually voltage at the point of common coupling of CCBG. The estimated phase angle is used to transform AC voltage and current signals to DC quantities. SRF-PLL is the most common and widely used PLL. Basic scheme of SRF-PLL is shown in Fig. 1(a) [14]. As shown in Fig. 1(a), abc-frame signals are transformed to dq-frame quantities using phase detector block. Then, q-axis quantity is passed through a loop filter (i.e. PI block) and voltage-controlled oscillator (VCO) to obtain the estimated phase angle (δ_{pll}). SRF-PLL employs a synchronous reference frame rotating at fundamental frequency of grid, to transform AC sinusoidal inputs of fundamental frequency (i.e. V_a, V_b, V_c) to DC quantities (i.e. V_d, V_q) as shown in Fig. 1(b). In Fig. 1(b), $\theta = wt + \delta_1$ where w is the fundamental frequency and δ_1 is the phase angle of voltage corresponding to fundamental frequency.



(a) Scheme of SRF-PLL

$$\begin{bmatrix} d \\ q \\ 0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

(b) Synchronous reference frame transformation

Fig. 1. Synchronous Reference Frame PLL

But, in presence of harmonics in V_a, V_b and V_c , the output quantities of transformation block will not be DC quantities [14]. Using the transformation matrix shown in Fig. 1(b), it can be calculated that V_q consists of harmonics in presence of harmonics in V_{abc} . The transformation of V_a, V_b and V_c , given in (1), results in V_d and V_q quantities as given in (2).

$$\begin{aligned} V_a &= V_1 \cos(wt + \delta_1) + V_n \cos(nwt + \delta_n) \\ V_b &= V_1 \cos(wt - 2\pi/3 + \delta_1) + V_n \cos(nwt - 2\pi/3 + \delta_n) \\ V_c &= V_1 \cos(wt + 2\pi/3 + \delta_1) + V_n \cos(nwt + 2\pi/3 + \delta_n) \end{aligned} \quad (1)$$

where, V_1 denotes the peak of voltage corresponding to fundamental frequency; V_n denotes the peak of voltage corresponding to n^{th} harmonic order; n denotes the harmonic order, w_{pll} is the estimated frequency by PLL, δ_n denotes the

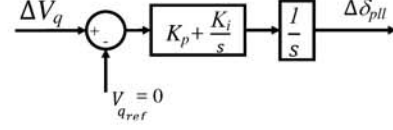


Fig. 2. Small signal model of SRF-PLL

phase angle of voltage corresponding to n^{th} harmonic order. Performing dq-transformation on the phase voltages,

$$\begin{aligned} V_d &= V_1 \cos((w - w_{pll})t + \delta_1 - \delta_{pll}) \\ &\quad + V_n \cos((nw - w_{pll})t + \delta_n - \delta_{pll}) \\ V_q &= V_1 \sin((w - w_{pll})t + \delta_1 - \delta_{pll}) \\ &\quad + V_n \sin((nw - w_{pll})t + \delta_n - \delta_{pll}) \end{aligned}$$

At steady state, $\delta_1 \approx \delta_{pll}$ and $w - w_{pll}$ is very less compared to $\delta_1 - \delta_{pll}$ [14],

$$\begin{aligned} V_d &\approx V_1 + V_n \cos((n-1)wt + \delta_n - \delta_{pll}) \\ V_q &\approx V_1(\delta_1 - \delta_{pll}) + V_n \sin((n-1)wt + \delta_n - \delta_{pll}) \end{aligned} \quad (2)$$

The impact of these harmonic components, considering perturbation in magnitude of harmonic voltage, can be analyzed using the small signal analysis of PLL. Based on perturbation theory, ΔV_q can be obtained as (3).

$$V_{q0} + \Delta V_q = (V_{n0} + \Delta V_n) \sin((n-1)wt + \delta_n - \delta_{pll0} - \Delta \delta_{pll}) + V_1(\delta_1 - \delta_{pll0} - \Delta \delta_{pll})$$

$$\begin{aligned} \Rightarrow \Delta V_q &= -V_{n0} \cos((n-1)wt + \delta_n - \delta_{pll0}) \Delta \delta_{pll} + \\ &\quad \Delta V_n \sin((n-1)wt + \delta_{pll0} - \delta_1) - V_1 \Delta \delta_{pll} \end{aligned} \quad (3)$$

$$= a(t) \Delta \delta_{pll} + b(t) \Delta V_n \quad (4)$$

where,

$$a(t) = -V_{n0} \cos((n-1)wt + \delta_n - \delta_{pll0}) - V_1;$$

$$b(t) = \sin((n-1)wt + \delta_{pll0} - \delta_1);$$

$V_{q0}, V_{n0}, \delta_{pll0}$ are initial values of V_q, V_n, δ_{pll} .

Small signal model of PLL, given in Fig. 1(a), is shown in Fig. 2. From Fig. 2, the state space model of PLL with V_q as input can be written as (5). Using (5) and (3), the state space model of PLL for harmonic stability analysis can be obtained as (6).

$$\begin{bmatrix} \Delta \dot{\delta}_{pll} \\ \Delta \dot{x}_{pll} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta \delta_{pll} \\ \Delta x_{pll} \end{bmatrix} + \begin{bmatrix} K_p \\ K_i \end{bmatrix} \Delta V_q \quad (5)$$

$$\begin{bmatrix} \Delta \dot{\delta}_{pll} \\ \Delta \dot{x}_{pll} \end{bmatrix} = \begin{bmatrix} K_p a(t) & 1 \\ K_i a(t) & 0 \end{bmatrix} \begin{bmatrix} \Delta \delta_{pll} \\ \Delta x_{pll} \end{bmatrix} + b(t) \begin{bmatrix} K_p \\ K_i \end{bmatrix} \Delta V_n \quad (6)$$

where, K_p and K_i are the parameters of PLL as shown in Fig. 2. Δx_{pll} is a state variable of PLL. It is to be noted that $a(t)$ and $b(t)$ are periodic with time period of $1/((n-1)w)$. The

small signal model of PLL is a Periodic Linear Time Varying (PLTV) System with period T .

$$a(t+T) = a(t); b(t+T) = b(t) \quad (7)$$

$$T = \frac{1}{(n-1)\omega} \quad (8)$$

B. Harmonic Stability Analysis

In this study, the harmonic stability of power system at n^{th} harmonic frequency is analyzed considering only the n^{th} harmonic frequency components of the voltages and currents of the system. Similar to the conventional stability analysis, all the elements of power system are modeled in the DQ-frame [15] i.e., synchronously rotating reference frame of the network. As the power system has voltages and currents corresponding to $n\omega$ frequency, the reference frame is also considered to be rotating at $n\omega$ frequency. The loads and transmission lines present in the power system are modeled in the similar way as done for fundamental frequency stability analysis [15]. The SGs are modeled as constant impedance loads. The impedance values for loads, transmission lines and SGs are calculated as given in [16]. The CCBGs are modeled considering the converter dynamics, filter dynamics and control loops of converters as given in [17]. The PLL dynamics are modeled as given in (6). It is to be noted that the small signal models of all the elements except for PLL can be obtained as Linear Time Invariant(LTI) systems. A small signal model for the entire power system under investigation can be obtained by cascading the models of all elements of the power systems [15]. The small-signal model for the entire power system can be written in a compact form as (9). The harmonic stability of the system can be evaluated by analyzing the system given in (9).

$$\Delta \dot{X} = A(t)\Delta X \quad (9)$$

where, $A(t)$ is the state matrix of the entire power system model.

As the PLL model is PLTV and rest of the elements in power system are of LTI in nature, $A(t)$ will be periodic with the same period as that of PLL model i.e., $A(t+T) = A(t)$. The stability of PLTV system can be analyzed using the Floquet coefficients or the Hill's determinant [18], [19] corresponding to the system. But these conventional methods to determine the stability of PLTV systems requires the computation of state transition matrix of the system. The computation of state transition matrix is a computationally demanding task and the difficulty amplifies as the order of power system increases. So in this paper, the dynamics of the power system in harmonic frequency domain is analyzed using a time varying eigen-value concept introduced in [20]. As the state matrix $A(t)$ is periodically varying with time, the eigen-values of the matrix also varies periodically with time.

$$A(t+T) = A(t) \implies \lambda_i(t+T) = \lambda_i \quad (10)$$

The possible cases that can occur due to the periodically varying eigen-values are shown in Fig. 3 where λ denotes

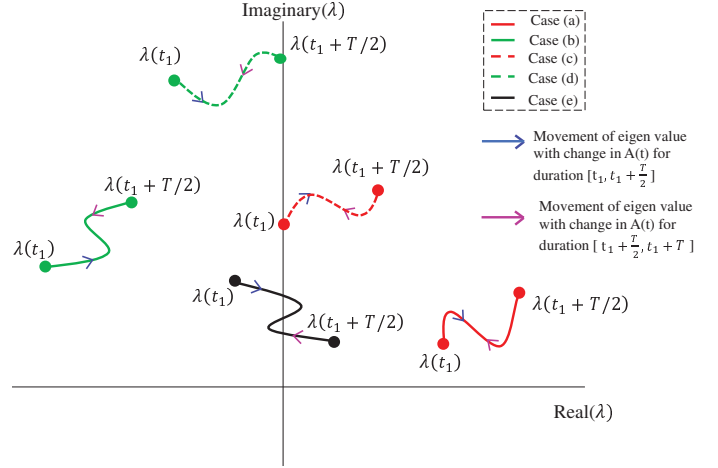


Fig. 3. Possible cases of eigen-values with periodically varying $A(t)$

eigen-values of $A(t)$. The trajectories of eigen-values shown in Fig. 3 are for illustrative purpose, the actual trajectories depends on state matrix $A(t)$. The dynamics of the power system under these possible cases are detailed below, with reference to the Fig. 3.

- Case (a): The eigen-values of $A(t)$ remain in the Right Half Plane(RHP) $\forall t \in [0, T]$. The power system will be unstable.
- Case (b): The eigen-values of $A(t)$ remain in the Left Half Plane(LHP) $\forall t \in [0, T]$. The power system will be stable.
- Case (c): The eigen-values of $A(t)$ stay either in the RHP or on imaginary axis. The power system will be unstable.
- Case (d): The eigen-values of $A(t)$ stay either in the LHP or on imaginary axis. Due to the eigen-values on the LHP the power system will be stable.
- Case (e): The eigen-values alter between LHP and RHP as $A(T)$ varies in the time period. When the eigen-values are in LHP the states of the power system move towards the steady state operating point of the power system. When the eigen-values are in RHP the states of the power system deviate from the steady state operating point. The real part of eigen-values along with the duration for which the eigen-values stay in the LHP and RHP decides the stability of the power system.

So, the stability of power system in harmonic domain can be evaluated by examining the variation of eigen-values in one time period.

III. RESULTS

A. PLL Small Signal Model in Harmonic Domain

This subsection presents results to validate the formulations presented in section II-A. The PLL block is investigated considering V_{abc} voltages with 1% harmonic content corresponding to 6^{th} harmonic frequency. The fundamental frequency of V_{abc} is considered to be 60 Hz. The equations (2), which are

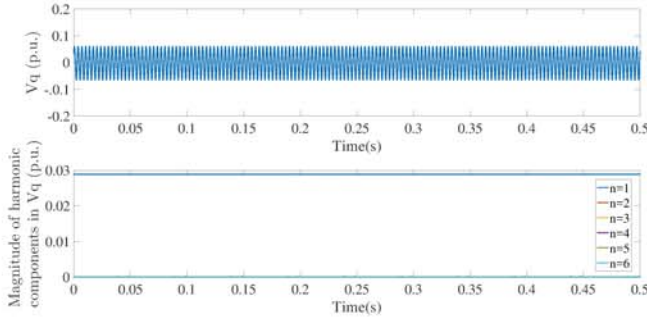


Fig. 4. Magnitude of Harmonic Components in V_q (in PLL reference frame)

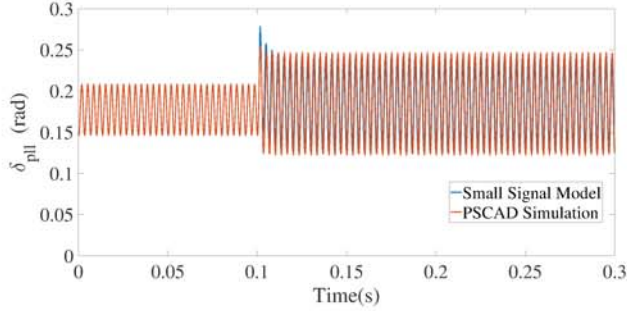


Fig. 5. Validation of PLL small signal model

the basis of the derived model are validated using PSCAD simulations. The obtained harmonic components in the V_q voltage are shown in Fig. 4, n denotes the harmonic order. It is clear from the figure that with 6^{th} order harmonics in V_{abc} the voltage V_q will have 5^{th} order harmonics after transformation from abc to dq reference frame.

The small signal model formulated in section II-A is validated through PSCAD simulations. The model given in (6) is excited by a step increase of 0.01pu in harmonic voltage magnitude at $t = 0.1s$. The state space equations are solved using MATLAB platform and the obtained result is shown in Fig. 5. PSCAD simulation is carried out using the SRF-PLL block with the same step change in the harmonic voltage. The obtained result from PSCAD simulation is shown in Fig. 5. From the Fig. 5, it can be concluded that the small signal model formulated in section II-A is suitable to study the dynamics of PLL in harmonic domain.

B. Power System Considered for Analysis

The standard IEEE-39 bus system is considered to perform the stability analysis in harmonic domain. The standard IEEE-39 bus system is modified to achieve the required level of penetration of PV and wind generation. The modified IEEE-39 bus system is shown in the Fig. 6. Parameters of SGs, transmission lines and loads are taken from [21]. Control and converter parameters of PV are adapted from [17], after applying appropriate scaling. WGs are modeled as per [22]. Control and converter parameters are taken from [22], after

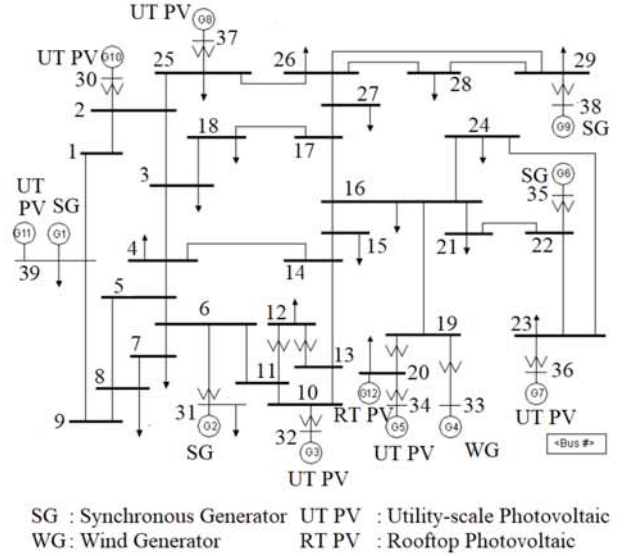


Fig. 6. Modified IEEE 39 bus system

appropriate scaling. PV labeled as G12 is a rooftop PV generator. The RE penetration considered for the analysis is given in TABLE I(a). The parameters for PI controller of PLLs in all the PV generators of the power system are set as per TABLE I(b). A 1% harmonic current injection into the network, at 6^{th} harmonic frequency i.e., 360Hz, is considered for all the PV generators of the power system to perform the harmonic stability analysis.

All the elements of the modified IEEE-39 bus system are modeled as discussed in section II-B. The state space model for the entire power system is expressed in the form of (9) and the time-varying eigen-values are calculated using MATLAB platform. The dynamics of power system in harmonic domain is analyzed at the operating condition as described in section III-B. The obtained state matrix $A(t)$ has 42 eigen-values. The time period of $A(t)$ is calculated as $T = 0.53 ms$ as per (8). The eigen-values with maximum real part and minimum real part computed over one time period are shown in Fig. 7. The variation in eigen-values is calculated in the intervals of $84\mu s$, i.e., $1rad$. The obtained results for two of the eigen-

TABLE I
BASE CASE DATA

	Real Power(MW)	Percentage contribution
PV	2810	45.8
WG	830	13.5
SG	2500	40.7
Loads	6097	-
Losses	43	-

(a) Load-Generation Scenario

Parameter	Value
K_p	50
K_i	900

(b) Parameters of PLL

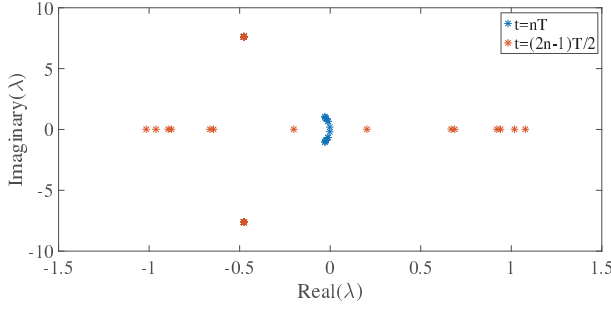


Fig. 7. Eigen-values with minimum and maximum real parts as $A(t)$ changes over one time period

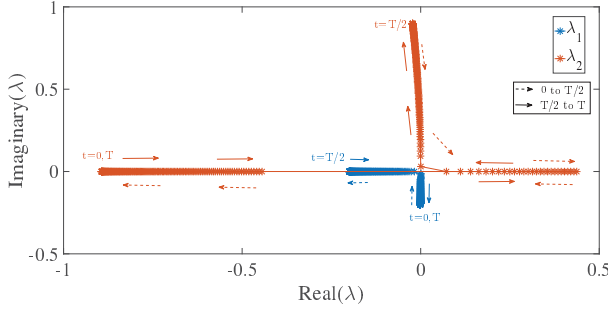


Fig. 8. Variation of eigen-values in one time period

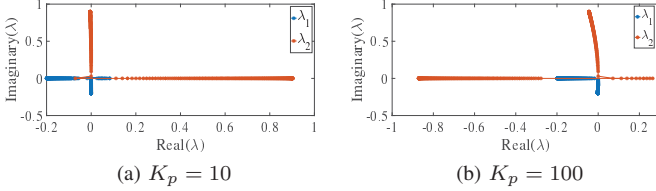


Fig. 9. Impact of K_p on harmonic stability

values of power system are presented in Fig. 8. It can be seen from the figure that the eigen-value λ_1 stays entirely in LHP where as the eigen-value λ_2 alters between the LHP and RHP. From the analysis of variation of all the eigen-values of the power system, it is observed that the eigen-values stay in LHP for longer duration compared to RHP. The variation of complete set of eigen-values for the power system couldn't be presented here due to the space constraint. It is observed that the other eigen-values of the power system also undergoes similar variations within a time period as that of presented in Fig. 8.

C. Impact of PLL Parameters

To analyze the impact of PLL on harmonic stability, PI block of PLL is represented as (11).

$$K_{gain} * K_p * \left(\frac{s + \frac{K_i}{K_p}}{s} \right) \quad (11)$$

where, K_{gain} is introduced to analyze the impact of variation of gain of the PI block.

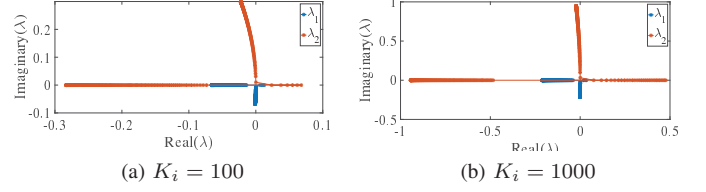


Fig. 10. Impact of K_i on harmonic stability

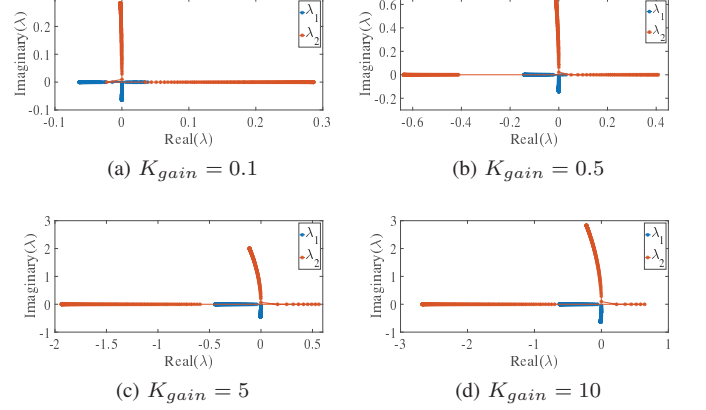


Fig. 11. Impact of PLL parameters on harmonic stability

1) *Varying K_p* : The proportional parameter of the PI block, K_p , is varied and the impact on harmonic stability is analyzed. The K_p parameter is varied from 10 to 100 with $K_i = 900$ and $K_{gain} = 1$, the obtained results at 10 and 100 are presented in Fig. 9. The Fig. 9(a) and Fig. 9(b) represents the variation of two of the eigen-values of the power system, where the rest of eigen-values also follow a similar trend as K_p is varied. It is observed that as K_p is increased, the eigen-values stay in LHP for longer duration improving the stability of power system in harmonic domain.

2) *Varying K_i* : The integral parameter, K_i is varied from 100 to 1000 with $K_p = 50$ and $K_{gain} = 1$. The Fig. 10 shows the variation in two of the eigen-values of the system at $K_i = 100$ and $K_i = 1000$. It is observed that the rest of eigen-values also follow a similar trend to that of Fig. 10(a) and Fig. 10(b) as K_i is varied. It is observed that as K_i is increased, the eigen-values stay in RHP for longer duration, affecting the stability of power system in harmonic domain.

From (11), it can be seen that as the K_p increases, the zero of the PI block moves closer to the origin there by decreasing the bandwidth of PI block. However, as the K_i increases, the zero of the PI block moves away from the origin there by increasing the bandwidth of PI block. From section III-C1 and section III-C2, it can be concluded that decreasing the bandwidth of PI block of PLL may improve the stability of power system in harmonic domain.

3) *Varying K_{gain}* : The factor K_{gain} is varied from 0.1 to 10 to analyze the impact on variation of eigen-values within a time period. The obtained results are shown in the Fig. 11. It can be seen that as the K_{gain} is increased the duration

TABLE II
RE PENETRATION LEVEL

Case No.	RE contribution	SG contribution
1	60%	40%
2	70%	30%
3	50%	50%
4	65%	35%

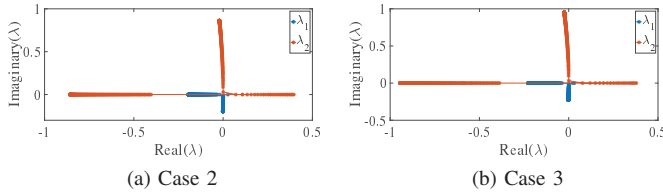


Fig. 12. Impact of RE penetration level on harmonic stability

for which the eigen-values stay in RHP is decreasing, there by improving the stability, and vice versa. From Fig. 11(a) through Fig. 11(d), it can be concluded that the higher values of PLL PI parameters may improve the stability of power systems in harmonic domain.

D. Impact of RE penetration level

The impact of RE penetration level on harmonic stability is analyzed by investigating the scenarios shown in TABLE II. The variation of eigen-values within a time period of $A(t)$ for case-2 and case-3 with reference to TABLE II are shown in Fig. 12(b) and Fig. 12(a). From the figures, it is observed that for the considered power system, the eigen-values tend to stay for longer duration in the RHP as the RE penetration level increases.

IV. CONCLUSION

The impact of PLL on harmonic stability of power systems is investigated in this paper. A new Linear Time Varying (LTV) state space model is formulated for PLL to carry out stability analysis in harmonic frequency domain. The state space model obtained for PLL is periodic in time, making the state space model of the whole power system a periodic LTV system. Due to the periodic state space model, the concept of periodic eigen-values is used to analyze the system stability in harmonic domain. The harmonic stability analysis is performed on a modified IEEE-39 bus system. For the investigated power system, it is observed that increasing the K_p and decreasing the K_i parameters improves the harmonic stability. The impact of renewable penetration level is analyzed for the modified IEEE-39 bus system. It is observed that increase in RE penetration level has a detrimental impact on harmonic stability of the considered power system. It is observed that the PLL parameters and renewable penetration level have impact on the harmonic stability of power system. However, the nature of the impact may vary depending on the

system. It is suggested that additional controllers are to be developed to mitigate the adverse impact of PLL on harmonic stability of renewable dominated power systems.

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