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Enhancing Small-Signal Stability of Intermittent Hybrid Distributed Generations

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***Abstract*—The variability of large-scale photovoltaic/wind hybrid distributed generation power integrated into the distribution system causes persistent system oscillations. The oscillations result in serious small-signal stability issues when these distributed generation units are not adequately optimised and the network dynamic variables are unconstrained as seen in the existing renewable power allocation planning works. In this paper, planning and design of optimal allocation (sizing, placement) and timing of intermittent renewable energy hybrid distributed generations such as photovoltaic and wind is being investigated with the ultimate goal of maximising the renewable power generated and absorbed into the distribution network within the required small-signal stability level at a minimum net present value of total cost. The problem is formulated as a stochastic mixed integer linear program where variables related to small-signal stability are constrained. The paper also evaluated the impact of these renewable generation output power variability on the small-signal stability of the IEEE-24 bus test system using eigenvalues analysis. The results indicate a profound improvement on the small-signal stability of the network, an increase in the quantity of renewable power absorbed and a significant reduction in the costs of emissions and electricity.**

***Index Terms*—renewable energy, distributed generation, mixed integer linear programming, distribution network, small-signal stability**

I. INTRODUCTION

The large-scale integration of intermittent hybrid distributed generation (IHDG) such as solar photovoltaic (PV) and wind into distribution system is expected to increase in the future years. This is due to favourable technological advancement, economic profitability, environmental benefits, resources complementarity and availability and increasing capability of these resources to meet high energy consumption [1]. However, the high degrees of variability and uncertainty of IHDG resources, coupled with the present setup of distribution networks which are generally passive, large-scale IHDGs integration is not technically visible. These bring about enormous challenges to the system operation, especially as relates to network small-signal stability and the amount of power absorbed into the network. These challenges are characterised by high variability of generated power due to resources intermittency or load in the system. The variability of power from IHDG units connected to the distribution system raises severe concerns over system oscillations which results in small-signal instability of the distribution system [2]–[4]. The authors in [5] posit that small-signal instabilities are the major cause of power system failures (outages). Also, the current passive setup of distribution network systems (DNSs) hinders maximum and effective integration of large-scale renewable energy DGs to the system since most renewable DG units are without reactive power compensation.

Meanwhile, research findings unequivocally agreed that different locations for the integration and sizes of intermittent DG units affect the system oscillation modes by either enhancing or worsening the small-signal stability of the network [6]. In essence, suboptimal type, improper sizing and improper location of IHDG units in a distribution system are a major causal of small-signal instabilities in the system. This is because suboptimal allocation or less effective optimization of IHDG units increases the extent of system oscillations and the effect of intermittencies on IHDG units connected to the distribution network systems [7]. Consequently, an effective planning and design of optimal allocation and timing of IHDGs in the distribution system is a viable methodology to solve the small-signal stability issues of the system.

Until now, a significant bunch of existing research works on planning and design of optimal allocation of IHDGs used mixed inter linear programming (MILP) due to its various advantages [8]. These works just considered static security and steady state stability [9]–[12], and not dynamic stability (small-signal stability). While in practice, dynamic stability issues often occur than the steady state ones during the renewable power integrations in DNSs. In [9], the optimal placement and sizing of renewable DGs with voltage stability constraints was studied for the distributed generations planning. The objective of the expansion planning is to minimise the net present value (NPV) of total cost of investment, production, maintenance energy losses and unserved energy. Reference [10] investigated the optimal sizing and placement of IHDGs with transient stability constraints to optimally assign solar PV and wind DGs into the DNS with a view to minimising the NPV of total cost. The authors in [11] and [12] used power transfer capability constraints in the optimal placement and sizing of the renewable energy resources DGs at the planning and design stage with the objective to maximise total DG capacity integrated into the networks at a minimised cost. However, these works did not consider the long term

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small-signal stability of the networks during the installation of IHDGs and operations of the network systems. They neglected the fact that small-signal stability of any power system is the prerequisite for that system to operate in practice [13].

In the literature, a study on the optimal allocation and timing of IHDGs with small-signal stability constraints is rare. The exiting works mostly assumed that the systems were small-signal stable during the integration of the renewable DGs in the DNS. They usually achieved minimum cost, but were not able to attain allowable small-signal stability level of the network after the integration. The main contributions introduced in this paper are as follows:

- In this paper, a new joint multi-stage mathematical optimisation formulation is presented for DNS expansion planning where sizing, placement, and timing of IHDG units and capacitor banks are modelled while the small-signal stability variables are explicitly constrained.
- Unlike the existing studies, this work evaluates the long-term dynamic small-signal stability in the planning optimisation of IHDGs allocation in a distribution network.

The resulting model is formulated as a stochastic mixed-integer linear programming optimisation problem as done in [8] to determine optimal sizes, locations and time of IHDG units in the distribution network. The typical pseudocode of a mixed integer linear programming formulation can be found in [8] for reference.

Consequently, the model for the integration of small-signal stability constrained IHDGs into a distribution network system along with the reactive power compensators (capacitor banks) that have capability to overcome the negative consequences of large-scale integration of IHDGs is developed. The ultimate goal of this optimisation work is to maximise the intermittent renewable power absorbed into the system at a minimum net present value cost while the small-signal stability is constrained to the required level.

The rest of the paper is arranged as follows: The mathematical background for modelling renewable resources and load is presented in Section II. Also presented is the power network model with renewable generator dynamic models and eigenvalue analysis of SSS together with the proposed optimisation model formulations. Section III presents the results and analysis of the case study used for the validation of the proposed model. The main conclusions are finally drawn in Section IV.

II. MATHEMATICAL BACKGROUND

A. Modelling of Renewable Resources and Load

1) Stochastic Modelling of Solar Irradiance and Wind Speed: This section models the renewable resources and uses Anderson and Darlington (AD) test to evaluate the best goodness of fits choosing Beta and Weibul distributions for solar irradiation and wind speed data respectively (Figures 1 and 2). where, $X_1 \leq \ldots \leq X_n$ are the controlled sample data and n is the number of samples taken.

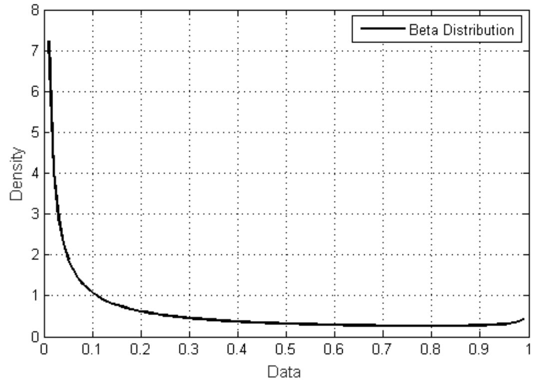

Fig. 1. Beta Distribution for Solar Irradiance Data

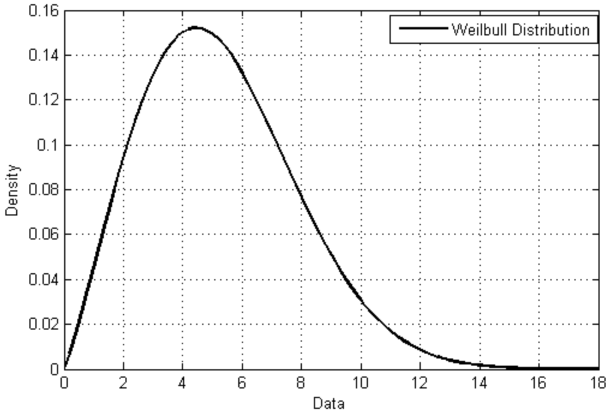

Fig. 2. Weibull Distribution for Wind Speed Data

2) Calculation of the Solar PV Module and wind Output Power: The output power of the PV module and a wind turbine corresponding to each state depending on the solar irradiance and ambient temperature, and wind speed of the site under study are calculated from (1) and (2), respectively.

$$P_{pv,h} = \begin{cases} \frac{P_r R_h^2}{R_{sc} R_c}; & 0 \leq R_h \leq R_c, \\ \frac{P_r R_h}{R_{sc}}; & R_c \leq R_h \leq R_{sc}, \\ P_r; & R_h \geq R_{sc}. \end{cases} \tag{1}$$

$$P_{wd,h} = \begin{cases} 0; & 0 \leq v_h \leq v_{ci}, \\ P_r(A + Bv_h^3); & v_{ci} \leq v_h \leq v_r, \\ P_r; & v_r \leq v_h \leq v_{co}. \\ 0; & v_h \leq v_{co}. \end{cases} \tag{2}$$

3) Modelling of Load Demand: The actual South African annual load profile [14] is computed to IEEE-24 bus system for implementation as a case study in this work. It presents the hourly load demand level for all the planning stages (three years in this case).

B. Power System Network Model

The dynamic network model is described by a set of nonlinear differential algebraic equations (DAEs), whose semi-explicit form is (3).

$$\begin{aligned} \dot{x} &= f(x_1, x_2, u_1) \\ 0 &= g(x_1, x_2, u_2) \end{aligned} \tag{3}$$

where x_1 and x_2 are vectors of state and algebraic variables respectively, and u_1 and u_2 are control inputs and exogenous parameters like load demand.

1) Dynamic Models of Power Generators: This section presents simplified classical voltage behind the constant reactance dynamic models of synchronous generator (SG) and renewable energy distributed generators (REDGs) such as photovoltaic (PV) and wind generators. A typical form of dynamic model with differential algebraic equations (DAEs) of different components of a distribution system is presented in (4). The network component (r) may be SG, PV farm or wind farm.

$$\begin{aligned} \dot{x}_r &= f_r(x_{1r}, x_{2r}, u_{1r}; \gamma_r) \\ P_r + jQ_r &= g_r\left(x_{1r}, x_{2r}, u_{2r}; \gamma_r\right) \end{aligned} \tag{4}$$

2) Dynamic Model of Synchronous Generator: A reduced order model of SG in state space representation is presented in (5) and (6).:
For generator buses $i = 1, \dots, m$.

$$\dot{\alpha_i} = \omega_i - \omega_s \tag{5}$$

$$\frac{2H_i}{\omega_s}\dot{\omega_i} = P_{mi} - \sum_{j=1}^{m+n} \frac{E_i' V_i}{X_{di}'} sin(\alpha_i - \theta_i) - D_i(\omega_i - \omega_s) \tag{6}$$

where the input P_{mi} is the mechanical power applied to the ith generator, $E_i' > 0$ is the constant internal voltage magnitude behind the transient reactance of the generator, V_i is the voltage magnitude and θ_i is the voltage angle at the bus i, $M_i = \frac{2H_i}{\omega_s} > 0$ is the inertia, $D_i > 0$ is the damping coefficient, $X_{di}' > 0$ is the transient reactance, $\alpha_i > 0$ is the rotor angle and ω_i is the angular frequency of the ith generator.

3) Dynamic Model of Photovoltaic Generator: The PV generator is modelled as constant voltage behind the transient reactance model [15], [16].
For generator buses $i = 1, \dots, m$.

$$\dot{I_{pvi}} = \frac{1}{\alpha L_{pv}} ln\left(\frac{I_L - I_{pv}}{I_s}\right) - \frac{1}{L_{pv}} V_{pvi} \tag{7}$$

$$\frac{2C_{dc}V_{dc}}{\omega}\dot{V_{pvi}} = V_{dc}I_{pvi} - E_{pvi}'I_q - E_{pvi}'I_d - D_{swl}V_{dc} \tag{8}$$

where solar array voltage, E_{pv}', is modelled as a series connection of a constant voltage source where $E_{pv}' = n_{pv}V_{pveq}$, D_{swl} is the conductance due to switching losses of DC/AC inverters.

4) Dynamic Model of Doubly Fed Induction (Wind) Generator: The DAEs that describe the dynamic behaviour of DFIG simplified model in state space representation are as follows:
For generator buses $i = 1, \dots, m$.

$$\frac{T_p}{K_p}\dot{\theta_p} = \phi(\omega_m - \omega_{ref}) - \theta_p \tag{9}$$

$$\frac{2H_m}{\omega_s}\dot{\omega_m} = P_{mi} - E_{wi}'I_q - E_{wi}'I_d - D_i(\omega_m - \omega_s) \tag{10}$$

C. Eigenvalue Analysis of Small-Signal Stability

Eigenvalue is used for small signal stability analysis. The oscillatory performance of a power system operating point is determined by computing all the eigenvalues of the state matrix (matrix A). If the real parts of all the eigenvalues of matrix A are negative in the complex plane, the system is very stable [13]. In a stable condition, the oscillation(s) that occurs in state variables due to small disturbance or imbalance in the system operating point dies out slowly over some time. However, the system is unstable if any of the eigenvalues of matrix A has a non-negative real part [13].

D. Formulation of the Planning Model

The ultimate objective of this proposed model is to enhance the small-signal stability while maximising the IHDG power absorbed into the distribution network at a minimum cost. The model is formulated as a Mixed Integer Linear Programming (MILP) optimisation problem.

1) Objective Function: The objective function to minimise the net present value (NPV) of total cost as in (11), and subject to linear constraints stated in Section II-D2.
Minimise,

$$\begin{aligned} C_T^{NPV} &= \sum_{t\in\Omega^t} \frac{(1+d)^{-t}}{d} C_t^I \\ &+ \sum_{t\in\Omega^t} (1+d)^{-t}(C_t^M + C_t^E + C_t^X) \\ &+ \sum_{t\in\Omega^t} \frac{(1+d)^{-T}}{d}(C_T^M + C_T^E + C_T^X) \end{aligned} \tag{11}$$

The first term in (11), the cost term C_t^I, is the total investment cost amortised in annual instalments throughout the lifetime of the installed components as done in [8]–[10]. The second term is the production and welfare costs through the time stages. This term consists of three cost terms vis-a-vis: total maintenance cost (C_t^M); total energy cost (C_t^E) and total emission cost (C_t^X). Lastly, the third term in (11) constitutes the net present value of the operation/production cost (maintenance and energy costs) and the emission (welfare) cost incurred after the last planning stage also known as end effect. This term depends on the operation/production and emission costs of the last time stage. It should be noted that all the cost terms expressed in (11) are estimated based on the principle of perpetual planning horizon [17].

The total cost in (11) comprises of amortised investment, maintenance, energy and emission costs with capital recovery $\frac{d(1+d)^{LT}}{(1+d)^{LT}-1}$ to weigh all the investment costs and return interest on capital invested for all the components [8].

2) Constraints:

1) Linearised Power Flow: AC Power Flow in the Network (Kirchhoff's Voltage Law) is linearised with the principle of fast decoupled power flow (FDPF) model, postulated in [18] ((12) - ((14)).

$$P_k = [B_{ij} * \theta_i] \tag{12}$$

$$Q_k = [B_{ij} * V_i] \tag{13}$$

$$V_i = V_i + \Delta V_i \tag{14}$$

2) Network Stability Constraints:

$$V^{min} \leq V \leq V^{max} \tag{15}$$

$$\theta^{min} \leq \theta \leq \theta^{max} \tag{16}$$

3) Power Flow Limits:

$$0 \leq \mid P_k \mid \leq P_k^{max} \tag{17}$$

$$Q_k^{min} \leq \mid Q_k \mid \leq Q_k^{max} \tag{18}$$

4) Active and Reactive Power Limits of Power from Transmission Feeders:

$$P_{\varsigma,s,h,t}^{SSmin} \leq P_{\varsigma,s,h,t}^{SS} \leq P_{\varsigma,s,h,t}^{SSmax} \tag{19}$$

$$Q_{\varsigma,s,h,t}^{SSmin} \leq Q_{\varsigma,s,h,t}^{SS} \leq Q_{\varsigma,s,h,t}^{SSmax} \tag{20}$$

5) Active and Reactive Power Limits of IHDGs:

$$P_{g,i}^{min} u_{g,i,t} \leq P_{g,i,(t)} \leq P_{g,i}^{max} u_{g,i,t} \tag{21}$$

$$Q_{g,i}^{min} u_{g,i,t} \leq Q_{g,i,t} \leq Q_{g,i}^{max} u_{g,i,t} \tag{22}$$

6) Active and Reactive Power Balance (Kirchhoff Current Law):

$$\begin{aligned} & P_{\varsigma,s,h,t}^{SS} + \sum_{g \in \Omega^{DG}} (P_{g,i,s,h,t}^{E} + P_{g,i,s,h,t}^{N}) \\ & + \sum_{in,k \in \Omega^i} P_{k,s,h,t} - \sum_{out,k \in \Omega^i} P_{k,s,h,t} \\ & = PD_{i,s,h,t} + P_{Lk,s,h,t} \end{aligned} \tag{23}$$

$$\begin{aligned} & Q_{\varsigma,s,h,t}^{SS} + \sum_{g \in \Omega^{DG}} (Q_{g,i,s,h,t}^{E} + Q_{g,i,s,h,t}^{N}) \\ & + \sum_{in,k \in \Omega^i} Q_{k,s,h,t} - \sum_{out,k \in \Omega^i} Q_{k,s,h,t} \\ & = QD_{i,s,h,t} + Q_{Lk,s,h,t} \end{aligned} \tag{24}$$

III. CASE STUDY

This section presents and discusses the results of the case to validate the proposed algorithm.

A. Network Data and Hypotheses

A 24-bus system is studied over a three-year planning horizon for testing the proposed model. The single line diagram and network data of IEEE-24 bus system can be found in many literature such as [19]. The assumptions and cost values used in this case study can be found in [8]. United States dollar ($) is the currency used in the simulation of this study.

B. Results and Discussions

For this study, the optimisations were implemented on an Acer Veriton with two Intel Core (TM) i5 650 processors at 3.20GHz and 16GB of RAM using MATLAB R2019a version. Optimality gap of 0.1% is achieved for the optimality of solutions while the computation time to obtain optimal solution is 22s. The IHDGs penetration limit, ϵ, of 30% is considered, which is well above the target level for South Africa for 2030 renewable projections [20].

1) Results of Optimal IHDGs Allocation Problem: The optimal solutions for IHDGs (solar PV and wind) and capacitor banks are presented in Tables I and II respectively. They show that larger percentage of the investment are done in the first stage. Higher NPV of costs for maintenance, energy and emission at the first stage than for the subsequent stages accounts for this. It is an indication of economic variability as more IHDGs are invested on in the first stage which allows the costs to reduce gradually throughout the planning horizon.

TABLE I
OPTIMAL INVESTMENT SOLUTION OF IHDGS FOR THE PLANNING HORIZON

IHDG Type	***Located Bus***	***Time Stages*** T1 $x_{g,i,t}$	T2	T3
Solar	3	19	30	43
Wind	3	72	98	127
Solar	19	9	9	9
Wind	19	46	48	50

TABLE II
OPTIMAL INVESTMENT SOLUTION OF CAPACITOR BANKS FOR THE PLANNING HORIZON

Located Bus	***Time Stages*** T1 $x_{cb,i,t}$	T2	T3
2	8	8	10
3	11	13	16
6	14	24	34
9	33	33	33
13	7	8	8
17	6	6	9
23	9	11	11
24	4	4	7

Table I shows that more wind DG units are integrated than solar PV units despite having equal parameters of integration. This is because wind generators have higher capacity factor than PV generators. The total capacities of IHDGs power (MW) installed each year is shown in Figure 3. The total of 338.6MW, 90.8MW and 102.5MW of renewable power are located in the network for the first, second and third stages respectively. The results from Table I, and captured in Figure 3 illustrate the complementarity of intermittent renewable generations. Consequent upon these results, the hybrid renewable are optimally allocated close to one another.

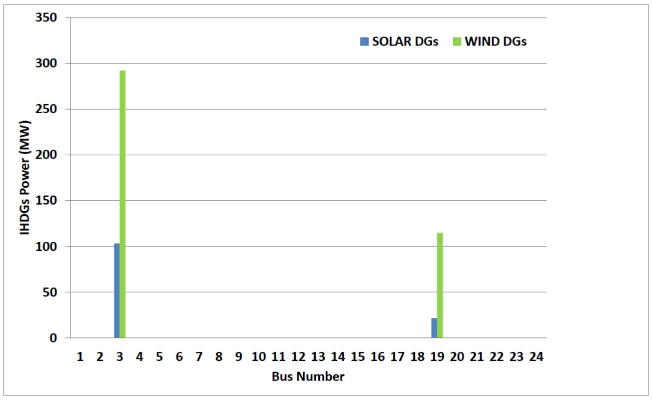

Fig. 3. Optimal locations and sizes of PV and wind power integrated throughout the planning horizon

Table II indicates that the optimal locations of capacitor banks are mostly on the buses with heavier loads and those close to the end of the network. This is a normal power system phenomenon where capacitor banks are installed to compensate the reactive power inadequacy in the system, thereby helping to enhance network voltage stability by keeping the voltage magnitude within the limits. The total capacity of capacitor banks invested in and installed through the planning stages are shown in Figure 4 to be 12.8MVAr, while 9.2MVAr, 1.5MVAr and 2.1MVAr are installed at each planning stage respectively. The addition of reactive compensators has greatly increased the capacity of renewable DG units that are integrated into the system to help in maintaining active and reactive power balance especially when reactive power absorbing generators are installed. Usually, the optimal capacity of IHDG units that could have been integrated would have been about 170MW.

In this study, the total load demand taken for IEEE-24 bus system is 345.4MWh at yearly demand growth estimates of 5% through the planning stages. The addition of 124.8MW PV farms and 407.1MW wind farms caused the electricity generation from coal-firing plants to reduce by 30% which gives total NPV investment costs of $\$25.5B$, $\$6.85B$ and $\$7.73B$ for the three planning stages respectively. Thus the overall total investment costs is $\$40.08B$. The total NPV cost for the whole planning periods is $\$78.7B$ while NPV costs of maintenance, energy and emission are correspondingly equals to $\$602M$, $\$211.76M$ and $\$3.1B$ respectively. Consequently, a total sum of $\$39.74B$ has been saved for installing a total of 531.9MW of intermittent renewable power to meet up with load demand that would have come from coal-firing generations.

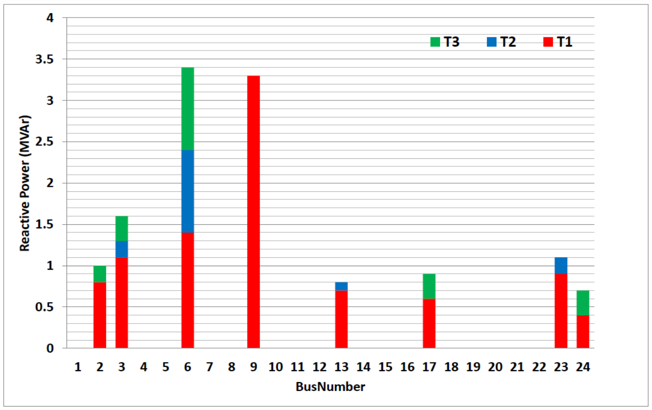

Fig. 4. Optimal capacities of reactive compensators located throughout the planning horizon

2) Evaluation of Small Signal Stability: Another important aspect of this IHDGs allocation optimisation analysis is the evaluation of the impact of their integration on the long term dynamic small signal stability of the distribution network. Figures 5 and 6 display samples of the eigenvalues plots of the network without intermittent distributed generators (base case), and with solar PV and wind DGs during every operational period throughout the planning horizon respectively.

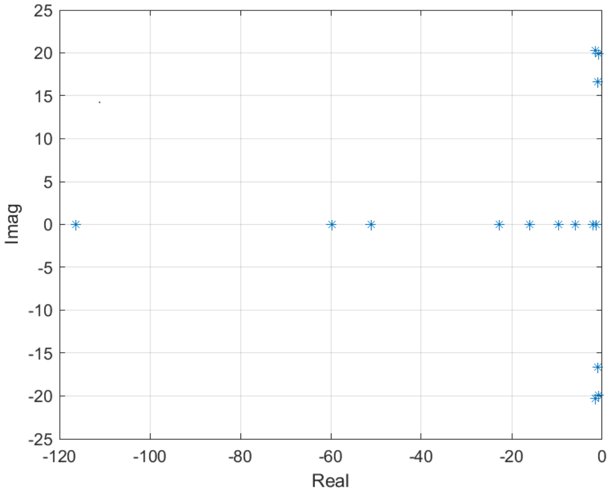

Fig. 5. Eigenvalues plot of IEEE-24 bus system (base case)

Figure 5 shows a typical eigenvalue assessment results for base case system. It is shown that the system has a very low margin to oscillatory instability. The eigenvalues of the base-case system situate away from the origin to the left half of the complex plane except the eigenvalues of quadrature transient internal voltages of generators 1, 2 and 3 that near oscillatory instability point. The damping ratio and oscillatory frequency are 0.0349 and 2.451Hz respectively.

Figure 6 shows that all the eigenvalues of the system are located away towards the left half plane during the integration of all these renewable DGs. The damping ratio of the critical mode improved from 0.0349 to 0.8792. The optimisation

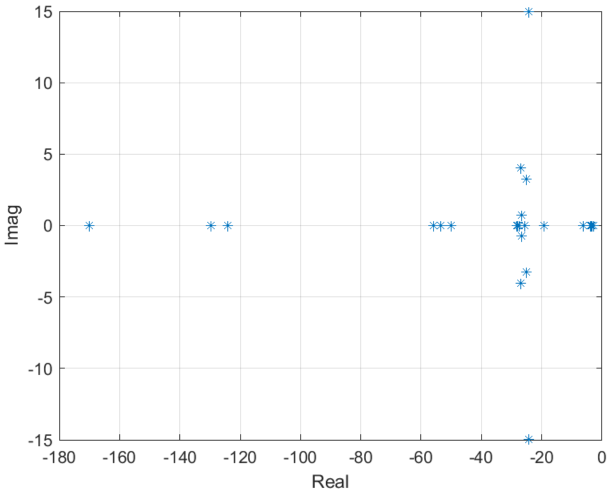

Fig. 6. Eigenvalues plot of IEEE-24 bus system with IDGs

results also show that as the voltage angle limits increase up until a maximum allowable value, the capacity of renewable generators installed increases, indicating increased renewable power absorptions into the network. That means more power flows in the network, and the network is more robust and could consume (contain) the effect of power variations (any small disturbances) from the intermittent renewable generations. It is also deduced that setting limits or constraints on the voltage angle helps in constraining and enhancing small signal stability of the distribution system.

IV. CONCLUSION

This work has developed a new MILP multi-stage mathematical optimization model considering large-scale integration of renewable DG in the distribution system. The integrated planning model simultaneously determines the optimal sizing, location and time of IHDGs units in distribution networks. The ultimate objective of this optimization work is achieved. That is, to maximize the intermittent renewable power absorbed by the system while maintaining the system small-signal stability at the required levels at a minimum cost possible. The standard IEEE 24-bus distribution system has been used to test the developed model and carry out the required SSS evaluation using eigenvalue analysis. Eigenvalue analysis results show improvements on the damping ratio and oscillation frequency of the critical mode. Optimising network dynamic variables shows that the impact of intermittent DGs power variability such as small-signal instability can be constrained to enhance the distribution network stability.

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