Study of Synchronous Condenser Impact in Jawa-Madura-Bali System to Provide Ancillary Services

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Abstract— **In recent years, the power grid trend is changing. The integration of renewable energy sources such as wind and photovoltaic into the existing grid is rapidly increasing. These global trends are expected to continue into the foreseeable future and could have a detrimental effect on grid performance. Problems in the grid will arise such as, reducing system inertia and reducing reactive power capacity. In many cases, these grid issues can be addressed with ancillary services. Presently in Indonesia, the necessity of reactive power and inertia were provide from conventional power plants by the state-owned company, PLN. The simulation in this paper will show the requirement of reactive power and system inertia from the synchronous condenser as ancillary services. The simulation is conducted on the Jawa-Madura-Bali System model, which is the most extensive system in the Indonesian power grid. The total capacity of photovoltaic and wind in the year 2025 is 1,430 MW, and the capacity of synchronous condensers as ancillary services is 2,152 MW in scattered locations. Synchronous condensers shift to a better voltage, and system stiffness will increase from 680 MW to 794 MW.**

Keywords*— *power system stability, power system planning, photovoltaic, wind energy

I. Introduction

Nowadays, in order to fulfill a green energy target, the development of renewable energy (RE) sources such as solar (photovoltaic) and wind turbine is commonly performed; therefore, the integration of these RE sources to an existing grid will become a global trend worldwide [1]-[2]. Currently, based on 2019 data in Indonesia, the total installed generation capacity is approximately 66,968 MW with the capacity of total RE (including hydro and geothermal) around 7,790 MW and its total energy production around 31,547 GWh (11.31%). The Government of Indonesia stated RE development by Presidential Decree about fuel mix portion target for NRE (New and Renewable Energy) to reach 23% in 2025[3].

Based on 10-year development planning (RUPTL 2019-2028) prepared by the state-owned utility company, PT Perusahaan Listrik Negara (PT PLN), the scheme of generation expansion planning, consist of steam power plants, gas power plants, and RE development. Most common RE development is solar (photovoltaic) and wind turbine with intermittent nature, which produces electricity in a fluctuating amount depending on natural conditions. In the implementation, this RE has dispatchable, uncontrollable, and intermittent nature [4]. These worldwide trends will continue to foreseeable future and will have a detrimental effect on power system performances. Some problems will arise in the power grid, such as reducing short circuit strength, reducing system inertia, reducing dynamic reactive power capacity, and reducing voltage and transient stability margins. These grid issues can be addressed with ancillary services. Generally, ancillary services can be classified as frequency support, voltage support, and system restore services, which respond to disturbances. These services are required by system operators to maintain system security.

A possible solution to provide ancillary services is the implementation of synchronous condenser (SC) technology. Ancillary services by definition can be describe as equipment to support and maintain reliable operations of the electric power transmission system by following the grid code [5]. Synchronous condensers have the ability to compensate reactive power and keep voltage stability in power systems for more than 50 years [6]. Another significant benefit is its contribution to the overall short circuit to the power grid and provides the inertia system.

Indonesia has several big systems and the biggest one is Jawa-Madura-Bali System. This condition leads to three conditions: 1) Jawa-Madura-Bali System will have big capacity development of PV and wind, comparing to other smaller systems, 2) several existing thermal power plants already obsolete in terms of merit order because of lower efficiency compared to the newest thermal power plant, and 3) the Jawa-Madura-Bali system has a problem with low voltage and reactive power management. This problem should be fixed by the implementation of big reactive power compensation.

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PLN, as a state-owned electricity company in electrifying Indonesia, has a subsidiary company to manage and operate the power plant. The operation of the Jawa-Madura-Bali System is regulated by the PLN P2B (Load Dispatching Center), while each power plant operated by a subsidiary, namely PT Pembangkitan Jawa Bali (PT PJB) and PT Indonesia Power (PT IP). Although, as a subsidiary company, the transaction process is considered as transaction between two companies; therefore, if there are transactions outside the energy (kWh), the scheme must be ancillary services scheme. The purpose of this paper is to review and analyze the impact of the synchronous condenser (SC) to compensate the reactive power and provide an inertia system to support the stability system, in the Jawa-Madura-Bali system in 2025 by utilizing subsidiary from PLN as ancillary services.

II. Basic Theory

A. Synchronous Condenser

Synchronous condenser (SC) is unloaded synchronous machines that connected to the transmission grid, usually via step-up transformers, but it does not supply active power in the steady-state condition [7]-[8]. The synchronous condenser could regulate voltage, have excellent fault-ride through capability, provide short circuit current and passive inertial response [7].

In reactive power management, the function to produce or absorb reactive power from the power grid was achieved by regulating the excitation current to control the grid's voltage or to keep the grid's power factor at a specified level [9]. Synchronous condenser installation and operation are identical to large electric machines. A single line diagram with a synchronous condenser is shown in Figure 1.

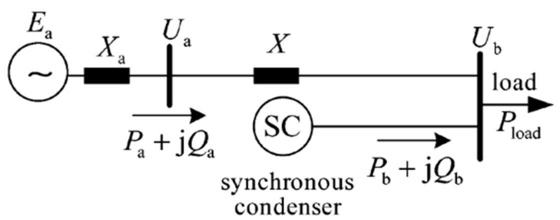

Fig. 1. Synchronous condenser connected to the grid [6]

Wind and photovoltaic are connected through the inverter to the power grid, and the inverter does not provide any inertia to the system, so their ability to support the transient changes in the power grid's frequency is minimal [10]. Traditionally, the power grid's inertia is provided by the kinetic energy of any rotating masses, which are electro-mechanically direct-connected to the grid [11], such as synchronous generators and synchronous condensers. It can be expressed as follows (1):

$$E_{rot} = \sum_{i=1}^{n} (S_i H_i) \tag{1}$$

where S_i is the rated MVA of the i-th synchronous generator H_i is the inertia constant of the i-th synchronous generator (second), n is the total number of committed synchronous generators, and S_{sys} is the rating of the specific power system. The equivalent system inertia constant of the network as represented by (2):

$$H_{sys} = \frac{E_{rot}}{S_{sys}} = \frac{\sum_i^n (S_i H_i)}{S_{sys}} \tag{2}$$

Higher system inertia will affect the robustness of power grid against transient changes in grid's frequency which give help to stabilize the system. In contrast, lower system inertia will reduce the support of transient changes in grid's frequency so a small disturbance causes more severe faults in systems [9]. These traits can be helpful to any power grid that has higher penetrations of renewable power sources, such as wind or photovoltaic [12].

Synchronous condenser is generally designed like other synchronous machine that has capability to maintain reactive power with proven, robust, and reliable solutions. The reactive power of Q and the real power of P related the relationship below, where S is the apparent power.

$$S^2 = P^2 + Q^2 \tag{3}$$

The movement of reactive power on an electrical network will influence voltage levels.

III. Simulation Method

A. Jawa-Madura-Bali System

Jawa-Madura-Bali System's peak load in 2019 is 27,973 MW. Total energy production in 2019 was 194.55 TWh and production from new and renewable energy was 14.99 TWh or 7.70% from total energy production. The majority in the generation system of the Jawa-Madura-Bali system are Coal-Fired Power Plant (CFPP), gas turbine power plant (GTPP), and combined cycle (CCGT). For the biggest capacity of renewable power plants are hydropower plants (HEPP) and geothermal power plants (GEPP).

The Jawa-Madura-Bali System has Extra High Voltage (EHV, 500 kV) for transmission backbone and HV (150 kV and 66 kV) as meshed transmission. The distribution system consists of Medium Voltage (MV, 20 kV) and Low Voltage (LV, 380 V) [3]. This paper only model the EHV and HV part of Jawa-Madura-Bali System and the simplified power system model of the Jawa-Madura-Bali system on Fig. 2. Referring to the Government of Indonesia to reach NRE mix of 23% [3], base case study in this paper uses future configuration of power system in 2025 with the following assumptions:

1. The peak load of the Jawa-Madura-Bali System in 2025 is 38,981 MW.
2. The total capacity for the Jawa-Madura-Bali system in 2025 is 56.494 MW (based on RUPTL 2019-2028) and the development of the transmission systems follow in RUPTL 2019-2025.
3. Photovoltaic and wind operate mainly produce on around noon, the other generation fleet will have loading at noon peak load.

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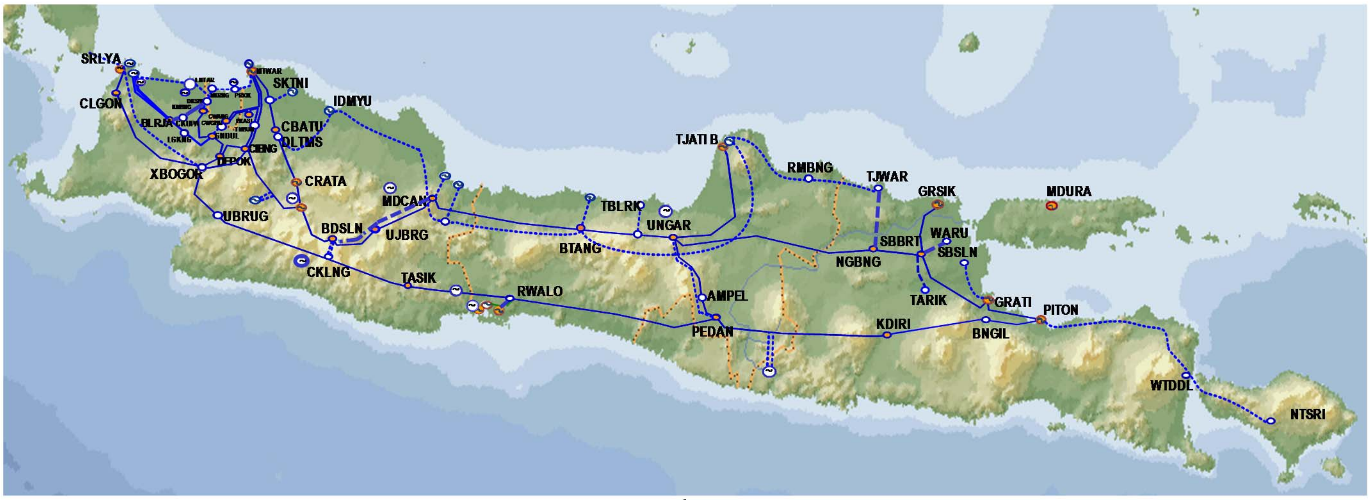

Fig. 2. Jawa-Madura-Bali 500 kV single line diagram [3]

B. Scenarios

To show the comparation of system stiffness and voltage regulation between different conditions, this paper conduct three scenarios:

1. Case in 2025 at 14:00 without renewable energy development (Base case) based on RUPTL 2019-2028.
2. Case in 2025 at 14:00 with renewable energy based on RUPTL 2019-2028 including the potential for the renewable energy source in Jawa-Madura-Bali system (RE development on RUPTL)
3. Case (2) with the addition of synchronous condenser in Jawa-Madura-Bali System (RE and synchronous condenser).

C. Dynamic Modelling

Even though there are 4 type of wind turbine model, currently type 3 (WT3) and type 4 (WT4) models are commonly used. The dynamic modeling of WT3 consists of the wind turbine as the generator component, the inverter as the exciter or voltage control mechanism, and its torque control due to the DFIG configuration [2] as the turbine model. Whereas WT4 consists of a wind turbine and its inverter as the exciter or voltage. The Type 3 and 4 wind turbine technologies are shown in Fig. 3.

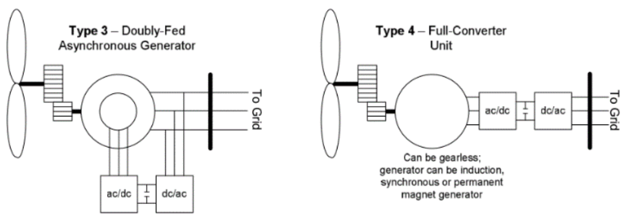

Fig. 3. The wind turbine type 3 and 4 technologies [13]

Dynamic modeling for wind turbine in this paper is (WT4). The ability to simulate performance changes due to solar irradiation is applied to the photovoltaic model. Both photovoltaic and wind uses similar control and inverter technologies to deliver energy to the grid from the point of DC connection to the grid connection [14]. The simulation uses PSS/E library as model for generator module and electrical control module of WT4 [14].

For the generic model for photovoltaic comprises the following modules:

- PVEU: electrical control module
- PVGU: power converter/generator module
- PANEL: linearized model of panel output curve
- IRRAD: linearized solar irradiance profile

The model is then integrated into the PSS/E simulation with the power converter, generator module and the electrical control module of the WT4. [14]. The GENROU machine model in PSS/E library was used for each synchronous condenser generator, which provides an excellent approximation of the synchronous condenser's dynamic behavior. [15].

D. The Disturbance

To create the effect of photovoltaic and wind integration to the grid, 25 power plants which represents all the power plant locations in the Jawa-Madura-Bali system was consecutively tripped.

The power plant type mostly are Coal Fired Power Plant, Combined-Cycle Power Plant, and Open-Cycle Power Plant because it would represent big generation units in Jawa-Madura Bali – System.

The power plant location is spread throughout Jawa-Madura-Bali System and based on the province such as Banten, DKI Jakarta, West Jawa, Central Jawa, and East Jawa.

E. Synchronous Condenser Location

The power plants that will be retired based on RUPTL 2019-2028 are assumed to be a synchronous condenser. The location of the synchronous condenser as ancillary services in the Jawa-Madura-Bali system such as:

- Jakarta North Western operate by PT PJB
- Jakarta North Eastern operate by PT IP
- Semarang Northern in Central Jawa operate by PT IP
- Surabaya Northern in East Jawa operate by PT PJB

The total capacity of the power plant, which is assumed to be a synchronous condenser, is 2,151 MW.

F. Location of Photovoltaic and Wind

The location and capacity and commercial operation date (COD) of photovoltaic and wind power plant based on RUPTL 2019-2028 are shown in Table I.

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TABLE I. LIST OF VARIABLE RENEWABLE ENERGY ON JAWA-MADURA-BALI SYSTEM IN 2025

Photovoltaic/Wind	2025 RUPTL Jawa-Madura-Bali System		
	Location	Capacity	COD
Photovoltaic/Wind	Banten	110	2022
Photovoltaic/Wind		110	2023
Photovoltaic/Wind		100	2025
Photovoltaic/Wind	West Jawa	5	2020
Photovoltaic		145	2021
Photovoltaic/Wind		100	2022
Photovoltaic		50	2023
Wind		100	2023
Photovoltaic/Wind		100	2023
Photovoltaic/Wind		100	2025
Photovoltaic	Central Jawa	50	2022
Wind		60	2022
Photovoltaic/Wind	East Jawa	50	2025
Photovoltaic/Wind		50	2021
Photovoltaic/Wind		50	2022
Photovoltaic/Wind		50	2024
Photovoltaic/Wind		100	2025
Photovoltaic	Bali	25	2020
Photovoltaic		25	2020
Photovoltaic/Wind		25	2025
Photovoltaic/Wind		25	2025

Until 2025, total photovoltaic and wind power plant which will be scattered connected to the Jawa-Madura-Bali system is 1,430 MW.

IV. SIMULATION RESULTS

A. Reactive Power Necessity Simulation

In the simulation function synchronous condenser as reactive power compensation, it will affect the amount of voltage on the bus. All 150 kV and 70 kV busses will be analyzed because those busses will be connected to the load through medium voltage bus. The comparison of three cases for 150 kV and 70 kV voltage level are shown in Fig. 4.

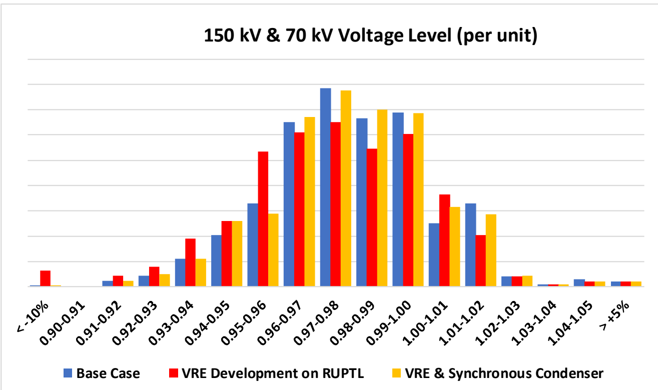

Fig. 4. Voltage in each bus 150 kV and 70 kV (pu)

Synchronous condensers will affect the voltage where there is a shift to a better voltage on the bus as in the base case scenario. However, in the case of VRE development on RUPTL, there are a few additional substations with operating voltage below standard. The synchronous condenser will play a role in improving the voltage locally around the synchronous condenser location.

B. System Inertia Necessity Simulation

The simulation to observe the effect of the synchronous condenser on system inertia is performed by finding the value of system stiffness in the Jawa-Madura-Bali system according to the scenario. The system stiffness in the Jawa-Madura-Bali system is defined as the amount of capacity (MW) decrease which cause 1 Hz frequency change.

There are three scenarios with 25 power plants that will instantaneously trip alternately; therefore, there will be total of 75 simulation results. The trip simulation is performed in the 2s to the 20s in dynamic simulation, and then the frequency will be observed for each simulation. Next, the frequency drop data for each power plant per scenario is collected and formed in a regression equation. The frequency drops for each scenario in MW per Hz is shown in Fig. 5.

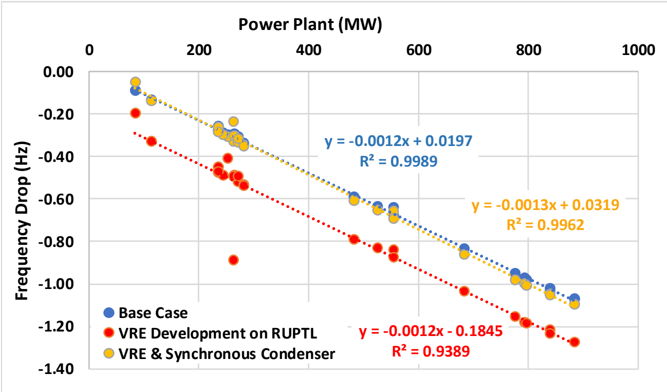

Fig. 5. Frequency drops for each scenario in MW per Hz

By equations (4)-(6), the system stiffness will be obtained in each scenario.

$$y = -0.0012x + 0.0197 \qquad R^2 = 0.9989 \tag{4}$$

$$y = -0.0012x - 0.1845 \qquad R^2 = 0.9389 \tag{5}$$

$$y = -0.0013x + 0.0319 \qquad R^2 = 0.9962 \tag{6}$$

By using equation (4)-(6) and value of y equal to -1 Hz, the value of x for each scenario in order (case1, case 2, and case 3) is 850 MW, 680 MW, and 794 MW.

Following the scenario with the photovoltaic and wind power plant connected to the Jawa-Madura-Bali system, it will cause a decrease in stiffness system compared to other scenarios since photovoltaic and wind power plants do not contribute inertia into the system. However, when synchronous condensers connect to the grid, it will increase the stiffness of the system from 680 MW to 794 MW. It means that synchronous condensers as ancillary services will contribute inertia to the system.

C. Effect of Synchronous Condenser Implementation

An example of synchronous condenser implementation for compensating reactive power and providing inertia is by operating any retired local power plant as synchronous condenser.

Furthermore, if there are many intermittent renewable power sources such as photovoltaic and wind where synchronous condensers contribute to inertia and improving short circuit strength.

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However, the deficiency of the synchronous condenser includes a higher level of losses, slower response time as compared to power electronic devices, and mechanical wear [16]. Nevertheless, if there is a lot of renewable energy integrated into the system, it will cause a significant drop in the system's short circuit strength. The synchronous condenser can also play a role in improving short circuit strength. In the year 2025, the Jawa-Madura-Bali system has enough reserve margin; therefore, the increase of losses due to synchronous condensers addition will not become significant problem. While those related to short circuit problems due to the involvement of many power plants, it is necessary to anticipate with adjustment of the transformer impedance in the synchronous condenser.

V. Conclusion

In this paper, the review and analysis of synchronous condenser (SC) impact to the compensate reactive power and provide an inertia system to support the stability system is presented. The simulation was performed with three scenarios, in which synchronous condensers are connected in four locations in the Jawa-Madura-Bali system. The synchronous condenser can supply the reactive power to maintain the voltage in the Jawa-Madura-Bali system. According to the simulation for three cases, it is found that synchronous condensers will increase the stiffness system from 680 MW to 794 MW when connected to the grid. Finally, the synchronous condensers as ancillary services from subsidiary company of PLN will contribute inertia and reactive power to the Jawa-Madura-Bali system.

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