Investigation of Passivity Behavior of Synchronous Generators Connected to Passive Network

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***Abstract*—Power electronics, storage and renewable technologies have led to a growing tradition of distributed power resources. While the emergence of distributed power resources provides improved control over the grid, it becomes necessary to analyze the stability of these devices in grid connected mode. It is desirable to provide a simple, robust stability criterion that can be checked locally, without the information of the entire grid. Passivity based stability criterion is well-suited for this purpose as the electrical transmission and distribution network to which these devices are connected is primarily made up of passive components. It is necessary to examine the passivity behavior of synchronous generators, which comprise a large part of the generation in modern grids. This paper presents the passivity behavior of a synchronous machine and the effect of its closed loop controllers on the passivity behavior. It has been observed that the non-passivity can be minimized if the controllers are tuned properly, but the generator is not passive over the entire frequency range. However, it has been observed that passivity can be achieved by encapsulating the generator with a portion of the passive network. Case studies have been carried out using detailed models of the synchronous generators and their controllers.**

Index Terms*—Positive Real Systems, Small Signal Stability, Controlled Interactions, Synchronous Generator Passivity, Power System Stabilizer Tuning, Droop Control Strategy.

I. Introduction

The advent of distributed power sources are integrated to the conventional grid using power electronic devices. This is in addition to conventional generation, and transmission controllers like HVDC and FACTS. Adverse interactions of these devices in the past have been reported in [1], [2]. The unified stability analysis of distributed systems poses some challenges such as (a) a large number of possible operating conditions and network topologies have to be considered, (b) addition of new devices would require a fresh examination of the system, and (c) the stability analyses would have to be coordinated centrally. The need for a *decentralized* or *local* stability criteria for any device connected to the grid seems very useful. A "passivity" based stability criterion for grid connectivity of controlled power injection devices has been presented in [3]. Although this approach is expected to be conservative, it is expected that this approach will simplify the stability analysis significantly.

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The criterion is based on the fact that a feedback system consisting of two or more "positive real" sub-systems is stable. Since the electrical network (transmission lines, transformers) is positive real (also passive), the passivity of the individual sub-systems becomes sufficient to ascertain stability of the system. Although the analytical models of these devices are sometimes not easy to obtain, it is interesting to note that passivity can be checked by examining the equivalent admittance or impedance matrices (assuming that the sub-systems are time-invariant). The proposed criterion of stability can be easily checked in the frequency domain in the D-Q variables (to obtain an LTI model). This is convenient as the frequency response of the small-signal model about an operating point can be obtained by using simulation based frequency scanning techniques or by using a black-box approach [4], [5] even when an analytical model is not easily extractable or available.

This paper presents the passivity (positive real) behavior of synchronous generators connected to a passive network. We also explore the impact of the various controllers on the passivity behavior of synchronous generators. Most attempts on passivity based control have been directed towards voltage source converter (VSC) based devices to behave as passive components using active damping strategies as reported in [3], [6], [7]. Since the electrical network is usually passive and the passivity criterion requires that all the control blocks need to be passive, it is imperative to check if the synchronous generators are passive or not. Although a passivity based controller design for synchronous generator has been reported in [8], [9], the analysis is restricted to simplified systems and dynamic controller realization (dynamic gain based on speed). This paper presents the passivity behavior of synchronous generators and how they are influenced by their controllers. The frequency response can be easily obtained using frequency scanning and therefore, it is very easy to check.

The paper is organized as follows: A brief discussion about positive real systems has been presented in Section II. The passivity behavior of a synchronous generator has been shown in Section III. Section IV presents an analytical verification of passivity behavior of the droop control strategy. The passivity behavior of a synchronous generator connected to a passive network have been examined and the results are presented in Sectionand V. The conclusions and future work are discussed in Section VI.

II. Positive Real Systems

A schematic of modern power systems has been shown in Figure 1. The transmission network is usually passive and different series and shunt connected sub-systems are connected to it.

The analysis of positive real (passive) systems is well-defined

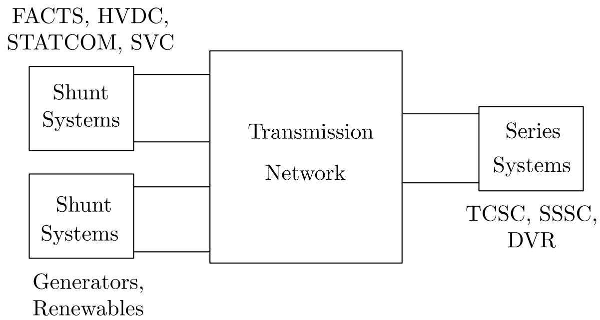

Fig. 1: Representation of a power system

for linear time-invariant (LTI) systems in terms of transfer functions. It is assumed that all power system components that are balanced and three-phase can be converted to a multi-input multi-output (MIMO) LTI system in the D-Q variables, and can therefore be represented by transfer function matrices.

Definition 1: Positive Real Systems: An $n \times n$ transfer function matrix $H(s)$ is positive real if [10]

- it is *Hurwitz* i.e. no poles are in right half s-plane (complex plane),
- $H(j\omega) + H^T(-j\omega) \geq 0$ for $\omega \in (-\infty, \infty)$.

It should be noted that a positive real system will be always stable but not vice-versa. Positive realness is useful because [10]:

- Sum of two positive real functions is also positive real i.e. parallel connection of two positive real systems is also a positive real system.
- Negative feedback connection of positive real systems is also positive real.

Definition 2: Passive Systems: An $n \times n$ transfer function matrix $H(s)$ is passive if $H(j\omega) + H^T(-j\omega) \geq 0$ for $\omega \in \mathbb{R}$.

It is interesting to note that all positive real systems are stable passive systems. The condition for positive realness and passivity of a transfer function $H(s)$ are equivalent if $H(s)$ is stable. We shall here assume that the stability of the individual sub-systems is ascertained at the current operating point. The positive realness of these sub-systems therefore becomes equivalent to the passivity of these stable sub-systems.

It can be easily shown that the passivity criterion implies that the rate of energy supplied to the system at any time instant is greater than the rate of change of energy stored in the system. For an electrical network, if the current entering a device is denoted as $i(t)$ and the voltage across the same is denoted as $v(t)$, then the instantaneous power supplied to the device is $v(t)i(t)$. Therefore, the impedance/admittance transfer function of an electrical network is expected to be passive. The key aspect that has to be kept in mind is that the device characteristics need to be passive in the absorption sense i.e. with the convention as the current is entering the device. The passivity (positive realness) can be checked as follows:

- Obtain the admittance frequency response of the sub-system $Y_g(j\omega)$.
- For every ω, calculate $Y_g^{\mathcal{R}}(j\omega) = Y_g(j\omega) + Y_g^T(-j\omega)$.
- Check the eigenvalues of $Y_g^{\mathcal{R}}(j\omega)$. It is to be noted that all the eigenvalues of a positive definite Hermitian matrix are positive. The sub-system is therefore passive iff all the eigenvalues of $Y_g^{\mathcal{R}}(j\omega)$ are non-negative for all ω.

The open loop system (electrical network) can be modeled as series and parallel combinations of R-L-C components. Since R, L, C components are positive real and such combination of positive real systems are also positive real, the open loop system is therefore positive real. However, the grid connected sub-systems like FACTS devices, HVDC links, synchronous generators with excitation systems, renewable based generation etc. need not be passive systems.

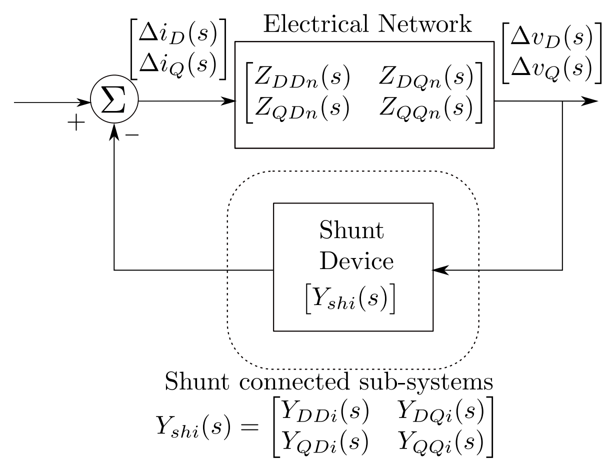

Fig. 2: Schematic of feedback structure in power systems (shown here for only one shunt connected device)

As already stated in [3], it is relevant to restate here that the stability criterion is

- Since the open loop system (electrical network) is positive real, the closed loop system will be stable if the shunt connected sub-system is also positive real[1].

It is interesting to point out that the criterion can be checked locally without detailed information of the grid. The small-signal admittance matrix of the device $(Y_{sh}(j\omega))$ has to be evaluated and has to be checked for passivity. Although the presence of non-linear components makes it hard to analytically elicit the frequency response of these devices, a pragmatic alternative is to obtain the same using frequency scanning techniques [4], [5]. We shall now focus on the passivity behavior of synchronous generators and the impact of different controllers.

[1] As discussed previously, the notion of passivity and positive realness is equivalent for stable sub-systems.

III. Passivity of Synchronous Generators

The passivity behavior of synchronous generators have been investigated here. The synchronous generator has been modelled using the detailed (2.2) machine model. Since the passivity behavior needs to be checked for the entire frequency range, the stator transients and the network transients are also modeled here. The power system stabilizer (PSS) and the automatic voltage regulator (AVR) are also modeled here.

TABLE I: Synchronous Generator Data

Synchronous Generator Parameters and Values							
x_d	x'_d	x''_d	x_q	x'_q	x''_q	H	f_B
0.2	0.033	0.0264	0.19	0.06	0.03	54	50 Hz
T'_{do}	T''_{do}	T'_{qo}	T''_{qo}	R_a	MVA_B	kV_B	x_l
8	0.05	0.4	0.04	0	100 MVA	20 kV	0.15
$V_t = 1.01\angle 3.66°$			$I_o = 6.92\angle -2.6°$ (injection into the grid)				
Static type AVR: $K_e = 200, T_e = 0.05$					PSS: $T_1 = 0.1, T_2 = 0.05$		
Reheat type steam turbine governor: $T_1 = 0.2, T_2 = 0.05, T_3 = 0.1$, $T_{co} = 0.4, T_{rh} = 10, T_{ch} = 0.3, f_{LP} = 0.4, f_{IP} = 0.3, f_{HP} = 0.3$							
Time constants are in seconds, other quantities: pu, if nothing mentioned							

The generator terminal voltage is being regulated by the AVR here. If the frequency scanning is performed at the generator terminals, it will create a situation where the terminal voltage (which is being regulated) is constantly perturbed externally. In order to avoid this inconsistency, the generating transformer is also included within the generator model and the frequency scanning has been performed consistently from the network side of the transformer. A schematic of the frequency scanning of a synchronous generator is shown in Fig. 3. Since the generators are usually made of passive components, they are expected to be passive by themselves. However, the presence of closed loop controllers often imparts the non-passive behavior. Therefore, it is expected that outside the controller bandwidths, these components should be passive. The frequency scan therefore needs to be performed up to around the controller bandwidths, usually around 100 Hz. The generator data has been given in Table I.

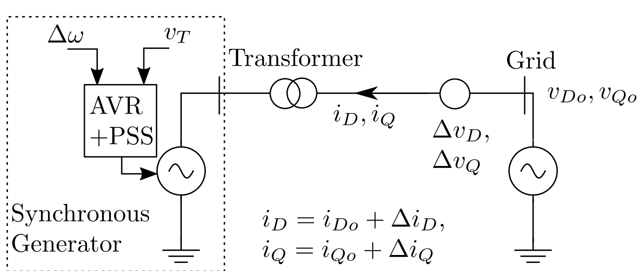

Fig. 3: Frequency scanning of synchronous machine

The frequency response of the generator admittance ($Y_g(j\omega)$) has been obtained. The passivity behavior can be checked by checking the positive definiteness of $Y_g^{\mathcal{R}}(j\omega) = Y_g(j\omega) + Y_g^T(-j\omega)$. The variation of the passivity behavior due to (a) PSS gain and (b) governor gain has been shown exclusively in the frequency ranges of interest. The overall frequency scan of the synchronous generator has been also shown.

A. Passivity Over The Higher Frequency Range

Before analyzing the effect of the different controllers on the passivity index of the synchronous machine model, we first look into the passivity behavior of the synchronous machine. The passivity behavior of the admittance function is given in Fig. 4. It can be seen that the synchronous machine is not passive in the low frequency range. The non-passivity (negative eigenvalue of $Y_g^{\mathcal{R}}(j\omega)$) is higher at the lower frequency range (swing dynamics range). It is very minimal in the mid-frequency range and finally becomes passive after around 77.1 Hz. The high frequency (beyond the controller bandwidth) behavior of the machine is found to be passive. This is expected as the component on itself comprises of passive components only. We shall now explore the effect

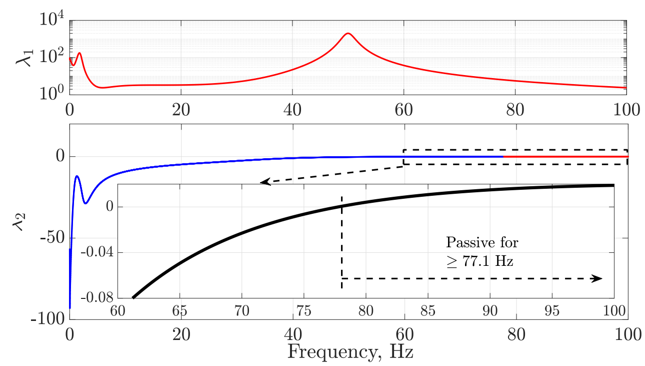

Fig. 4: Eigenvalues of $Y_g^{\mathcal{R}}(j\omega)$

of the variation of (a) PSS gain, and (b) governor gain on the passivity behavior of the synchronous generators.

B. Variation of PSS Gain

The frequency response of the synchronous machine admittance has been obtained for different values of PSS gain. Since the PSS is expected to influence the swing frequency (0.2 - 2 Hz) range only, the frequency response in this range has been shown here only. The variation of the eigenvalues of $Y_g^{\mathcal{R}}(j\omega)$ for different values of PSS gain is shown in Fig. 5. It can be seen from the plots that one of the eigenvalues is positive while the other is negative. From the passivity perspective, the negative eigenvalue of $Y_g^{\mathcal{R}}(j\omega)$ is of more concern.

It can be seen that the progressive change in PSS gain impacts the frequency response only in the swing frequency range (as shown in Fig. 5). Furthermore, the gradual change in the PSS gain also shifts the frequency at which the negative peak (λ_1) happens. It can be concluded that as the PSS gain K is varied from 0 to 24, the negative peak of λ_1 initially reduces up to some point (shown with solid line) and then again starts to increase. The optimal PSS gain has been selected as the value of K for which the negative peak of λ_1 is minimum in the swing frequency range. The optimal PSS gain has been observed to be around 14. It can be

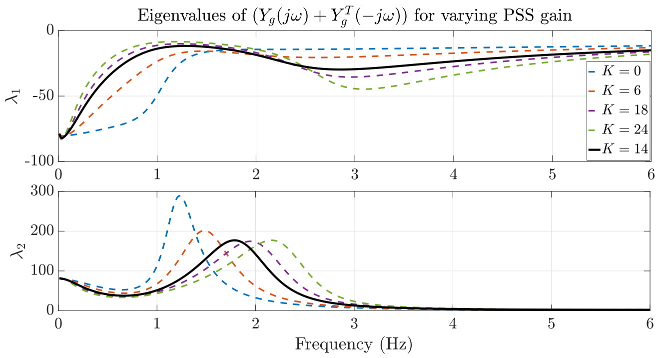

Fig. 5: Eigenvalues of $Y_g^{\mathcal{R}}(j\omega)$ for different PSS gain

seen that the synchronous generator is not passive in the swing frequency range. However, proper tuning of the PSS parameters can ensure that the non-passivity in this frequency range is minimal.

The root loci of the synchronous generator model for varying PSS gain is shown in Fig. 6. For clarity, the poles that are most affected (higher sensitivity) due to variations in the PSS gain are plotted. It can be seen that although two of the poles (complex conjugate pair) move toward left for increasing PSS gain, another pole moves towards the right. It can be seen that the value of PSS gain which causes non-passivity to be minimal also gives a relatively optimal (all poles with reasonably good damping) placement of all the poles (lesser/higher gain causes at least one of the poles to be too close to the imaginary axis). It is therefore imperative that if the PSS tuning is done based on passivity considerations, it will also ensure that the closed loop poles are not placed too close to the imaginary axis.

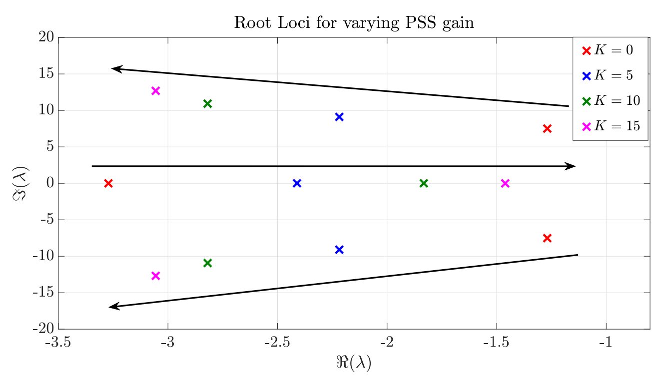

Fig. 6: Root loci of $Y_g(s)$ for different PSS gain (most sensitive eigenvalues)

C. Variation of Reheat Type Governor Gain

The frequency response of the synchronous machine admittance for different values of the governor gain has been shown here. A reheat type steam turbine governor has been modeled here. The variation of the eigenvalues of $Y_g^{\mathcal{R}}(j\omega)$ in the very low frequency range for different values of governor gain is shown in Fig. 7. As the governor is of much slower dynamics, it is expected to impact the very low frequency range only. Therefore, the frequency response of the very low frequency (up to around 0.1 Hz) range has been shown here in detail. It can be seen from the plots that one of the eigenvalues is positive while the other one is negative. From the passivity perspective, the negative eigenvalue of $Y_g^{\mathcal{R}}(j\omega)$ is more significant.

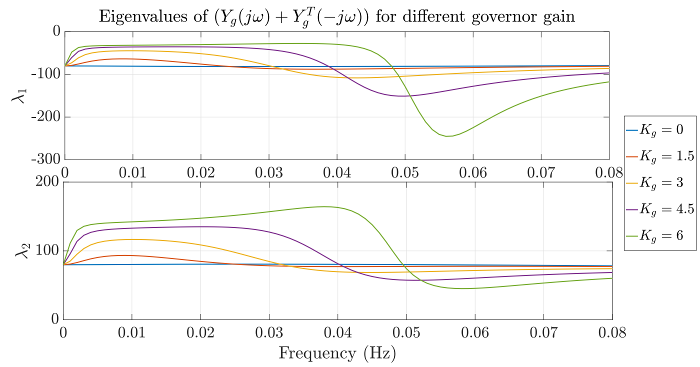

Fig. 7: Eigenvalues of $Y_g^{\mathcal{R}}(j\omega)$ for different governor gain

It can be seen that the progressive change in governor gain impacts the frequency response of the synchronous generator in the very low frequency range (up to about 0.1 Hz). It can also be seen in Fig. 7 that the non-passivity index (largest negative eigenvalue) in this frequency range does not improve by variation of the governor gain. The extent of non-passivity in fact increases as the governor gain is increased. An analytical verification of this behavior has been presented in Section IV.

Conclusions: We have seen the passivity behavior of the synchronous machine and the effect of the controllers on its passivity indices. We have seen that the governor does not improve the passivity index in the very low frequency range. The passivity indices can be improved significantly in the swing frequency range by proper tuning of PSS components. We shall now look into the analytical verification of the non-passivity of droop control strategy, which is the simplified model of synchronous generators with governors. The applicability of droop control strategy is not only limited to synchronous machines, but are used for different power-electronic converters also.

IV. Simplified Analysis of Passivity of Droop Control Strategies

An analytical verification of the passivity behavior of droop control strategy has been shown here. As synchronous machines (with governor) behave similarly as droop control strategies at steady state, this analysis will also provide the analytical verification of the passivity behavior of synchronous machines (with governors) in the very low frequency range. Let us consider a synchronous machine is connected to the grid and at the equilibrium point, it is withdrawing (flowing into the device) active and reactive power of P_o and Q_o respectively.

Let the equilibrium bus voltage phasor is $\bar{v}_o = v_{Qo} + jv_{Do}$. For the simplicity of analysis, let us assume that the D-Q transformations are done w.r.t. to the local bus voltage angle. Under this condition, we have $v_{Do} = 0$. The current flowing into the device is given by

$$i_{Qo} + ji_{Do} = \frac{P_o - jQ_o}{v_{Qo}}$$

The droop control strategy is defined as in (1).

$$\Delta P = K_p \Delta\omega, \quad \Delta Q = K_q \frac{\Delta V}{V_{nom}} = K_v \Delta V \tag{1}$$

where $K_p, K_q > 0$ and V_{nom} is the nominal voltage magnitude of that bus. With the current convention taken as going into the generator, the active and reactive power withdrawn by the machine are given as

$$P = v_D i_D + v_Q i_Q, \quad Q = v_D i_Q - v_Q i_D \tag{2}$$

Linearizing (2) and equating to (1), we get

$$\begin{bmatrix} v_{Do} & v_{Qo} \\ -v_{Qo} & v_{Do} \end{bmatrix} \begin{bmatrix} \Delta i_D \\ \Delta i_Q \end{bmatrix} + \begin{bmatrix} i_{Do} & i_{Qo} \\ i_{Qo} & -i_{Do} \end{bmatrix} \begin{bmatrix} \Delta v_D \\ \Delta v_Q \end{bmatrix} = \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{3}$$

The polar co-ordinates (V, ϕ) of the voltage phasor are related to the cartesian co-ordinates(v_D, v_Q) as

$$\phi = \tan^{-1}\left(\frac{v_D}{v_Q}\right), \quad V = \sqrt{v_D^2 + v_Q^2} \tag{4}$$

Linearizing (4) about the equilibrium point (v_{Do}, v_{Qo}), we get

$$\begin{gathered} \frac{\partial \phi}{\partial v_D} = \frac{v_{Qo}}{V_o^2}, \quad \frac{\partial \phi}{\partial v_Q} = -\frac{v_{Do}}{V_o^2} \\ \frac{\partial V}{\partial v_D} = \frac{v_{Do}}{V_o}, \frac{\partial V}{\partial v_Q} = \frac{v_{Qo}}{V_o} \end{gathered} \tag{5}$$

It is to be noted that the subsript o denotes the equilibrium value of the corresponding variable. The equations are now written in Laplace domain with the conventional notation 's'. Putting $v_{Do} = 0$ and substituting (5) in (1), we get

$$\begin{bmatrix} \Delta P(s) \\ \Delta Q(s) \end{bmatrix} = \begin{bmatrix} \frac{K_p s}{v_{Qo}} & 0 \\ 0 & K_v \end{bmatrix} \begin{bmatrix} \Delta v_D(s) \\ \Delta v_Q(s) \end{bmatrix} \tag{6}$$

Substituting (6) in (3) and putting $v_{Do} = 0$, we get

$$\begin{aligned} Y_{DQ}(s) &= \frac{1}{v_{Qo}} \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \frac{K_p s}{v_{Qo}} - i_{Do} & -i_{Qo} \\ -i_{Qo} & K_v + i_{Do} \end{bmatrix} \\ &= \frac{1}{v_{Qo}} \begin{bmatrix} i_{Qo} & -(K_v + i_{Do}) \\ \frac{K_p s}{v_{Qo}} - i_{Do} & -i_{Qo} \end{bmatrix} \end{aligned} \tag{7}$$

For the system to be passive, we need to check the positive definite-ness of $Y_{DQ}^{\mathcal{R}}(j\omega) = Y_{DQ}(j\omega) + Y_{DQ}^T(-j\omega)$ for all ω. It can be seen that

$$\begin{aligned} &Y_{DQ}^{\mathcal{R}}(j\omega) = Y_{DQ}(j\omega) + Y_{DQ}^T(-j\omega) \\ &= \frac{1}{v_{Qo}} \begin{bmatrix} 2i_{Qo} & -(2i_{Do} + K_v) - j\frac{K_p\omega}{v_{Qo}} \\ -(2i_{Do} + K_v) + j\frac{K_p\omega}{v_{Qo}} & -2i_{Qo} \end{bmatrix} \end{aligned}$$

For a Hermitian matrix to be positive definite, all the leading principal minors have to be positive. Therefore, one can alternately check the positive-definiteness of a Hermitian matrix by calculating its "upper-left $k \times k$ sub-marices", for $k = 1, 2.., n$, where n is the size of the matrix. For the 2×2 matrix $Y_{DQ}^{\mathcal{R}}(j\omega)$ here, the leading principal minors are

$$\Delta_1 = 2\frac{i_{Qo}}{v_{Qo}}, \Delta_2 = -\frac{4i_{Qo}^2}{v_{Qo}^2} - \left[\left(\frac{2i_{Do+K_v}}{v_{Qo}}\right)^2 + \left(\frac{K_p\omega}{v_{Qo}^2}\right)^2\right]$$

It can be observed that at any operating condition, $\Delta_2 \leq 0$. It is to be noted here that since all the leading determinants of positive definite Hermitian matrices have to be positive, the negativity of Δ_2 ensures that $Y_{DQ}^{\mathcal{R}}(j\omega)$ is not positive definite. Therefore, the droop control strategy is not passive and also not positive real in the defined set of input-output variables. The expressions also explain the increase in non-passivity of synchronous generators in the very low frequency range with increasing governor gain. It can be seen that as K_p is increased, the determinant becomes increasingly negative. Having discussed the passivity behavior of synchronous machine and the impact of its associated controllers, we shall now look into the passivity behavior of a synchronous generator interfaced to a passive network.

V. Effect of Network Encapsulation on the Passivity of Synchronous Generator

It has been observed in the preceding discussions that although a synchronous generator behaves as a passive device in the higher frequency range (beyond the controller bandwidths), the behavior is non-passive in the low-frequency range. The variation of controller parameters like PSS gain, governor gain can at most reduce the extent of non-passivity, but can not eliminate it completely.

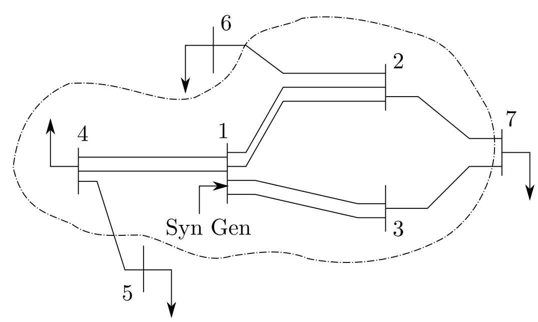

Fig. 8: Encapsulating network topology

We now try to investigate into the passivity behavior of a synchronous generator and the enclosed network. Since the electrical transmission network consists of passive elements such as R, L and C components, it is expected to be passive as combination of passive components are also passive. Since the synchronous generator by itself is not entirely passive, we try to "*encapsulate*" the synchronous generator with a part of the transmission network and check if the composite system is passive from the boundary buses. A schematic of the encapsulation idea has been demonstrated in Fig. 8.

A network layout enclosing the synchronous generator has been shown in Fig. 8. The synchronous generator (used for the earlier inspections) is located at bus 1. It is to be noted that by synchronous generator, the combination of the synchronous generator and the generating transformer is meant. Therefore, bus 1 here actually represents the secondary bus of the generator transformer. A transmission network has been constructed around the synchronous generator and the network parameters are provided in Table II. The load shown at bus 4 is modelled as constant impedance type load, therefore having a passive behavior in the selected input-output pair.

TABLE II: Network Data

Network Line	Series impedance (pu)	Shunt B (pu)
1-2	0.022+j0.22	j0.33
1-3	0.022+j0.22	j0.33
1-4	0.002+j0.02	j0.03
2-6	0.002+j0.02	j0.03
3-7	0.022+j0.22	j0.03
2-7	0.002+j0.02	j0.03
4-5	0.002+j0.02	j0.03
Note: For parallel lines, the network data for each line is given.		

The network data is now combined along with the synchronous generator to check the passivity behavior of the combined system. Let the buses be decoupled into the set of p peripheral buses and $n-p$ internal buses. With re-ordering the admittance matrix such that the peripheral buses appear first, the network admittance transfer function can be written as

$$\begin{bmatrix} I_p \\ I_{n-p} \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} V_p \\ V_{n-p} \end{bmatrix}$$

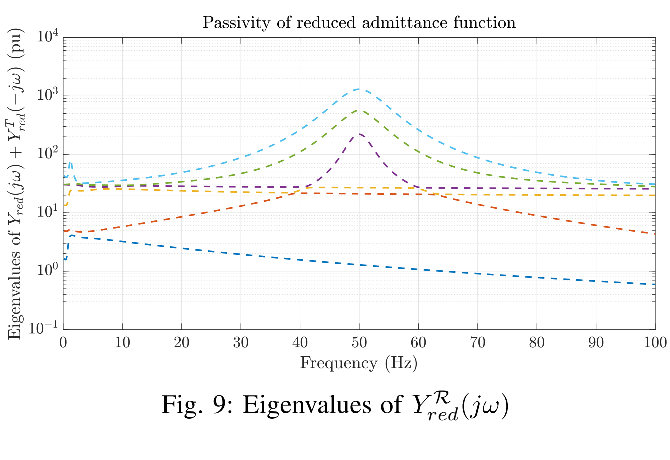

Fig. 9: Eigenvalues of $Y_{red}^{\mathcal{R}}(j\omega)$

The passivity of the network as seen from the boundary buses is now investigated. The reduced admittance transfer function of the network from the peripheral buses is

$$Y_{red}(s) = Y_{11}(s) - Y_{12}(s)\left(Y_{22}(s) + Y_{sg}(s)\right)^{-1} Y_{21}(s)$$

where $Y_{sg}(s)$ is the admittance of the synchronous generator. For the network in Fig. 8, the peripheral buses being selected are $\{5, 6, 7\}$. The synchronous machine frequency response has been evaluated with the machine data and operating condition provided in Table I. The passivity of the reduced admittance transfer function has been checked and the eigenvalues of $Y_{red}^{\mathcal{R}}(j\omega) = Y_{red}(j\omega) + Y_{red}^T(-j\omega)$ have been shown in Fig. 9. It can be seen that all the eigenvalues of $Y_{red}^{\mathcal{R}}(j\omega)$ are positive indicating passivity of the reduced system.

VI. Conclusions and Future Work

This paper presents the passivity behavior of synchronous generators. The effect of commonly used controllers on the passivity behavior are also presented here. It has been observed that although these devices are made of passive components, the presence of closed loop controllers often make their behavior non-passive. Although these devices are non-passive over a wide frequency range, their passivity indices can be improved in specific frequency range by suitable tuning of the controllers. The non-passivity at low frequency range due to the governor action has been checked analytically and the conclusions are independent of the operating condition. It is also shown that these devices can be encapsulated by a part of the passive transmission network, thereby eliciting a passive behavior from the boundary buses of the sub-network. We aim to develop a "passivity based stability" criterion to propose a (a) simple to use, (b) robust and (c) sufficient stability criterion for the grid operators in order to design the devices appropriately while ensuring small-signal stability of the system.

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