Analysis of Control Conflict between UPFC Multiple Control Functions and Their Interaction Indicator

H. F. Wang, M. Jazaeri, and Y. J. Cao

Abstract: Interactions among multiple control functions of a UPFC installed in a power system have been observed in power system simulation and been reported in authors' previous publications [1,2]. This paper presents new analytical results about these observed interactions and concludes that they are due to the control conflict between the series and shunt part of the UPFC, which are connected through the internal common capacitor inside the UPFC. Investigation in the paper reveals, for the first time as far as the authors are aware of, that the linkage pattern of UPFC series and shunt part decides whether the control functions implemented by the UPFC series and shunt part conflict each other or not. This linkage pattern of UPFC series and shunt part can be described by the flow of active power through the UPFC at steady-state operation of the power system. Hence in order to predict the possible interactions among multiple control functions of the UPFC, an interaction indicator is proposed in the paper which is the direction and amount of active power flow through the internal link of the UPFC series and shunt part at steady-state operation of the power system. This proposed interaction indicator can be calculated from power system load flow solution without having to run simulation of the power system with UPFC controllers installed. By using the indicator, the interactions among multiple control functions of the UPFC caused by badly set controller's parameters are excluded. Therefore the indicator only identifies the possible existence of inherent control conflict of the UPFC.

Keywords: Unified power flow controller (UPFC), interactions of UPFC control, power system control.

1. INTRODUCTION

Since its proposal [3], the Unified Power Flow Controllers have attracted wide interests from power system engineers and researchers [4]. Many aspects of UPFC operation have been investigated with constructive results published [5-17]. Reckoning that the provision of multiple control functions is one of the major advantages of a UPFC, in [1,2] the authors studied the interactions among UPFC multiple control functions from the viewpoint of multivariable control theory. This is because UPFC multiple control functions, i.e., voltage regulation, active and reactive power flow control, plus DC voltage regulation, effectively form a typical Multi-Input Multi-Output (MIMO) control system, as shown by Fig. 1.

Fig. 1 shows the conventional arrangement of Single-Input Single-Output (SISO) controllers for each of UPFC control functions. According to multivariable control theory [1,2], this arrangement is inherently defective because interactions among different control channels can lead to system instability under certain conditions, even though each individual SISO controller can operate satisfactorily. Indeed, examples of such worst cases have been reported by authors in [1,2], where individually UPFC controllers had been designed satisfactorily, but failed to operate jointly because of their interactions. However, reasons causing the failure of joint operation of UPFC multiple control functions are not explored in [1,2] and the physical explanation from the viewpoint of power system operation is not given. The interactions have been observed only by running power system simulation when multiple UPFC controllers are designed and installed in the power system [1,2]. Hence this result cannot tell whether the interactions are due to the internal connections among the UPFC multiple control functions or caused by badly set parameters of UPFC controllers.

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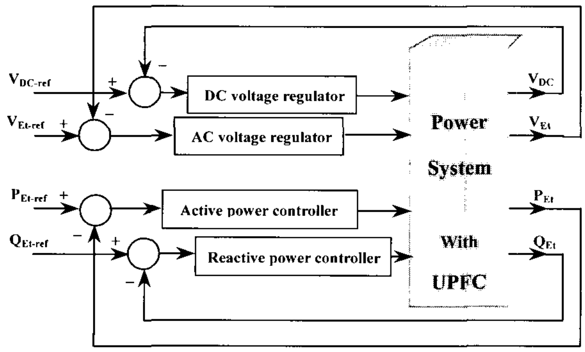


Fig. 1. Four-input four-output UPFC control system.

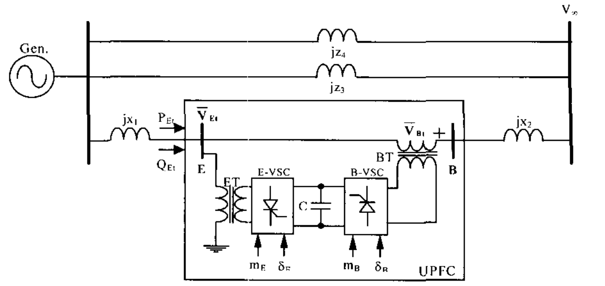


Fig. 2. A single-machine infinite-bus power system installed with a UPFC.

investigation on the interactions of UPFC multiple control functions. Based on the analysis of UPFC operation principle, it is concluded that the interactions are due to the control conflict between the series and shunt part of the UPFC, which are connected through the internal common capacitor inside the UPFC. Studies in the paper reveal, for the first time as far as the authors are aware of, that the linkage pattern of UPFC series and shunt part decides whether the control functions implemented by the UPFC series and shunt part conflict each other or not. This linkage pattern of UPFC series and shunt part can be described by the flow of active power through the UPFC at steady-state operation of the power system. Hence this provides a physical explanation of interactions of UPFC multiple control functions in terms of power system operation.

In order to predict the possible existence of interactions among UPFC multiple control functions without having to design UPFC controllers firstly and then to run power system simulation, this paper proposes an interaction indicator. The proposed indicator is the direction and amount of active power flow through the internal link of UPFC series and shunt part at steady-state operation of the power system. It can be calculated from power system load flow solution without having to run simulation of the power system with UPFC controllers installed. By using the indicator, the interactions among multiple control functions of the UPFC possibly caused by badly set controller's parameters are excluded. Hence it only identifies the possible existence of inherent control conflict between UPFC multiple control functions.

2. ANALYSIS OF CONTROL CONFLICT BETWEEN UPFC SERIES AND SHUNT PART

Without loss of generality, in this section the control conflict between UPFC series and shunt part is analysed based on a simple single-machine infinite-bus power system. More complicated case of an example multi-machine power system is presented in the next section which gives the results exactly as same as those presented in this section. Fig. 2 shows the single-machine infinite-bus power system where a UPFC is installed on one of three parallel transmission lines connecting the generator and infinite busbar. Parameters of the power system are given in Appendix.

The UPFC is assigned three control functions. They are the regulation of AC voltage at the shunt busbar E, V_{Et}, active and reactive power flow along the transmission line where the UPFC is installed, P_{Et} and Q_{Et}. In order for the UPFC to operate normally, a fourth controller is needed to regulate the DC voltage across the capacitor inside the UPFC [4,6]. The conventional selection of control signal of the UPFC for these four UPFC controllers is (1) the modulation ratio of UPFC shunt converter, m_E, is for the AC voltage regulator; (2) the modulation phase of UPFC shunt converter, δ_E, is for the DC voltage regulator; (3) the modulation ratio of UPFC series converter, m_B, is for the reactive power regulator; (4) the modulation phase of UPFC series converter, δ_B, is for the active power regulator. Fig. 3 shows the detailed arrangement of these four UPFC controllers, which are all Proportional-Integral (PI) controllers.

For the four SISO UPFC controllers, interactions can lead to system instability as reported in [1,2] and as it can be shown by the following demonstration example again.

In this demonstration example, each of UPFC controllers was designed one by one in a sequence: (1) DC voltage regulator was designed firstly when all other three controllers were not in service; (2) Then AC voltage regulator was set with DC voltage regulator in service and other two not; (3) Active power regulator was designed with DC and AC voltage regulator in service and the reactive power regulator not; (4) Finally, reactive power regulator was designed with all other three designed regulators in service. This design sequence was arbitrarily chosen and Fig. 4 shows the simulation results to assess the controllers' performance to a step change of control reference signal. From Fig. 4 we can see that these UPFC controllers all operated satisfactorily.

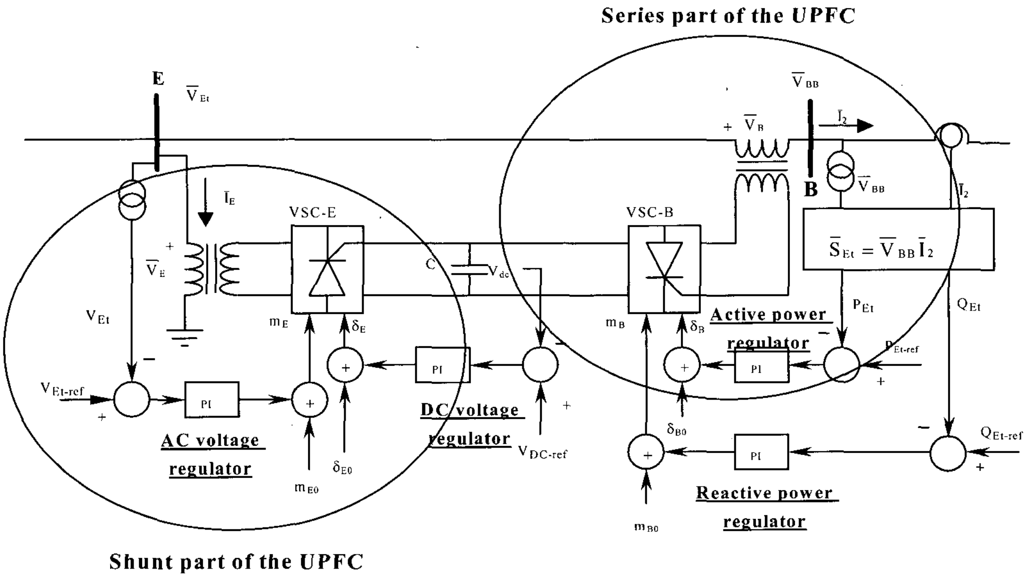
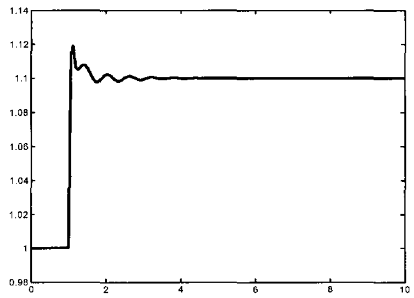
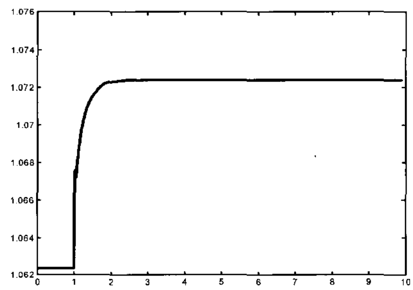


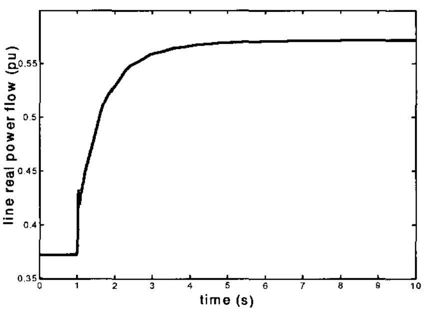
Fig. 3. Arrangement of four UPFC controllers.



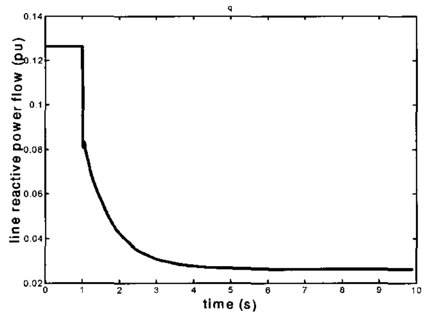
(a) DC voltage control performance.



(b) AC voltage control performance.

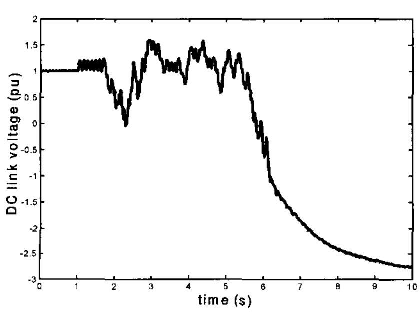


(c) Active power control performance.

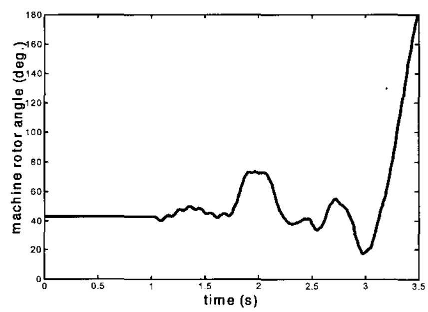


(d) Reactive power control performance.

Fig. 4. Simulation to examine UPFC controller's per-formance.



(a) Step response of DC voltage regulator.



(b) Response of generator rotor angle.

Fig. 5. Simulation to examine control performance of UPFC DC voltage regulator when it operated jointly with AC voltage regulator and active power regulator.

However, when these UPFC controllers were tested for their joint operation, system instability occurred. Fig. 5 shows the test result specifically in the third step of the previous design where DC, AC voltage regulator and active power regulator operated jointly, achieving a satisfactory design of active power regulator as it is shown in Fig. 4(c). However, Fig. 5 shows the simulation result to re-assess the control performance of the DC voltage regulator, which had been designed and assessed previously. Obviously we observed the operation failure of DC voltage regulator, leading to the loss of system stability. From the viewpoint of control theory, this phenomenon can be explained clearly. It is because when the DC voltage regulator was designed, the active power regulator was not in service and hence its impact on the DC voltage regulator was not considered. In fact, in this case this impact is fatal, leading to system instability. This is the worst case of control interactions.

Authors have tested numerous designs with different design sequences and have found that this type of interactions exist between the DC voltage regulator and active power regulator as well as between the AC voltage regulator and reactive power regulator. Hence it makes the authors somehow to believe that the interactions may be because the internal connection between UPFC series part and shunt part (which are indicated in Fig. 3) and UPFC series and shunt control functions somehow conflict each other along this connection. However, results presented in Figs. 4 and 5 cannot distinguish the effect of electric connections between UPFC series and shunt part from that of badly set parameters of some UPFC controllers to confirm the author's belief. Therefore, the following analysis on the connection between UPFC series and shunt part has been carried out by carefully studying the pattern of active power flow inside the UPFC.

Fig. 6 shows a simplified illustration of UPFC configuration given in Fig. 3, where series and shunt part of the UPFC is represented simply by the series voltage source $\bar{V}_B$ and shunt voltage source $\bar{V}_E$ respectively. The step-down shunt transformer is modelled by a reactance jx_E. At steady-state operation, active power input to the UPFC, P_{Et}, arrives at UPFC series busbar B through two channels, the direct channel and internal channel, as shown in Fig. 6, i.e., $P_{Et} = P_{direct} + P_{Internal}$. The amount of active power flow through the UPFC internal channel, $P_{Internal}$, decides the electric connection between the series and shunt part of the UPFC. When $P_{Internal} = 0$, the series part of the UPFC neither absorbs active power from nor supplies active power to the power system and the phase between $\bar{V}_B$ and the line current $\bar{I}_2$ is 90 degrees. This is the case that the

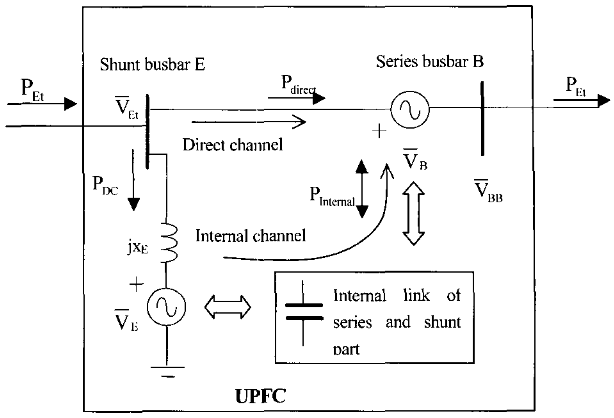
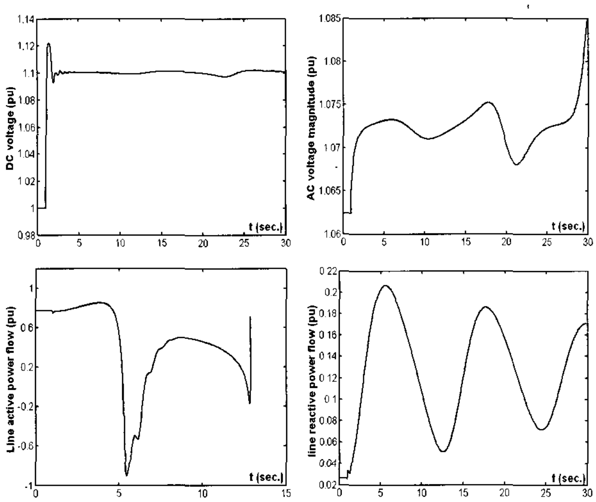


Fig. 6. Simplified representation of UPFC configuration.

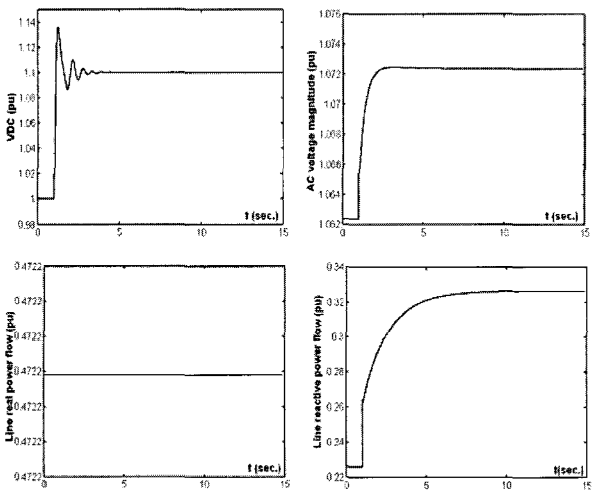
series part of the UPFC operates independently from the shunt part as a reactive power source [4,6], because it does not need active power support from the shunt part. Electrically, in this case, UPFC series and shunt part are two independently operating units, supplying reactive power to or absorbing reactive power from the power system. Hence we should expect that this is the case when there exist no interactions between the control functions of the UPFC series and shunt part. Fig. 7 presents the confirmation to this analytical conclusion from simulation.

In Fig. 7, design of four SISO UPFC controllers were completed one by one in a sequence as introduced previously when simulation results of Figs. 4 and 5 are given. Fig. 7(a) shows the results of step response of each controller when all four UPFC controllers are in joint operation. From Fig. 7(a) we can see that system instability occurred. For the exactly same design of UPFC controllers, we changed the UPFC operation to the operating condition with $P_{Internal}$=0. At this operating condition, control performance of the same UPFC SISO controllers were examined again as shown in Fig. 7(b). From Fig. 7(b) we can see that these UPFC controllers designed in sequence without considering their interactions worked satisfactorily in joint operation. This confirmed that $P_{Internal}$=0 results in no direct electric connection between UPFC series and shunt part and hence the control interactions disappeared.

On one hand, $P_{Internal}$ decides whether the series and shunt part of the UPFC are directly electrically connected or not as discussed above. On the other hand, the direction of $P_{Internal}$ determines whether the control functions of UPFC series and shunt part conflict each other or not, because inside the UPFC, there exists another active power flow. This second active power flow, P_{DC} as shown in Fig. 6, is due to the DC voltage controller implemented by the UPFC shunt part to charge the capacitor in order to maintain the normal operation of the UPFC.



(a) UPFC controllers' joint operation leads to system instability.



(b) UPFC controllers' joint operation at $P_{Internal}$=0.

Fig. 7. Simulation to confirm that $P_{Internal}$=0 results in the disappearance of UPFC controllers' interaction.

Since $P_{Internal}$ is regulated by UPFC active power controller, flow direction of $P_{Internal}$ and P_{DC} indicates whether control functions of UPFC series and shunt part conflict each other or not. If $P_{Internal}$ is in the same direction of P_{DC} from UPFC shunt part to series part, control functions of UPFC series and shunt part electrically pose no conflict requirement. Hence we should not expect high possibility of interactions between UPFC series and shunt part control functions. We define this is the case of positive $P_{Internal}$. On the other hand, however, if $P_{Internal}$ flows in the opposite direction of P_{DC} from series part to shunt part, we shall see conflict requirement of different control functions, resulting in possible control interactions leading to poor control performance. This is the case that $P_{Internal} < 0$.

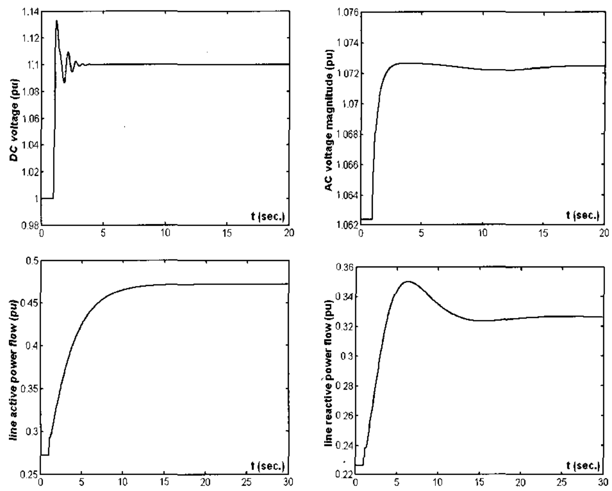


Fig. 8. Simulation results when $P_{Internal}$=0.03 p.u. >0.

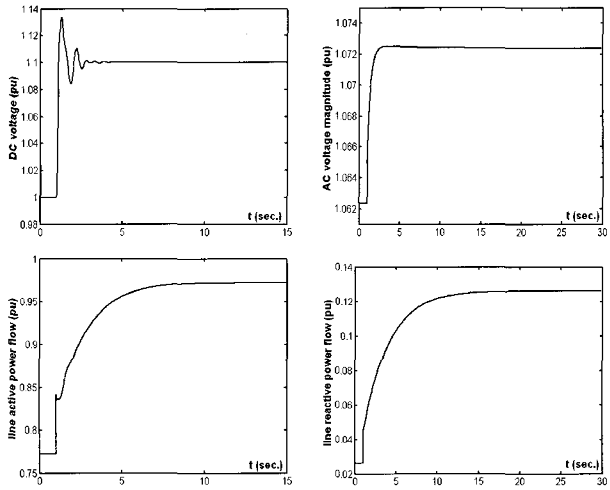


Fig. 9. Simulation results when UPFC DC voltage regulator is connected to an external battery.

To confirm the analysis above, authors have carried out huge amount of calculation and simulation for the same design of four SISO UPFC controllers demonstrated previously in Figs. 4, 5 and 7. Figs. 8 and 9 give two typical simulation results. When the UPFC worked at the operating condition with $P_{Internal}$=0.03 p.u. > 0, control performance of four UPFC SISO controllers was examined from their step response as shown by Fig. 8. From Fig. 8 we can see that the joint operation of UPFC controllers provides satisfactory results and there are no serious interactions observed. While the UPFC worked at a different operating condition with $P_{Internal}$ = -0.06p.u. < 0, simulation results are given in Fig. 7(b) showing serious interactions leading to system instability. For this case of $P_{Internal}$ = -0.06p.u. < 0 (Fig. 7(b)), in order to demonstrate that the interactions are indeed due to the conflict of $P_{Internal}$ flow against P_{DC} flow, we deliberately set up an external battery to supply P_{DC} to the capacitor inside the UPFC instead of from the power system. By doing so, the conflict between $P_{Internal}$ and P_{DC} flow had been avoided as far as the UPFC connecting to the power system is concerned. Simulation results with this setting up are presented in Fig. 9. From Fig. 9 we can see that the interactions disappeared.

From the analysis and demonstration above, we can propose that $P_{Internal}$ is used as an interaction indicator. If $P_{Internal} > 0$, we expect low possibility of serious interaction problem; If $P_{Internal} < 0$, we expect high possibility of interactions; $P_{Internal}=0$ indicates that there will be no interaction among UPFC multiple control functions. Obviously, calculation of $P_{Internal}$ does not needs the UPFC controllers to be designed and installed. Hence this proposed interaction indicator only identifies the interactions due to the electric coupling of UPFC control. It successfully excludes the impact of UPFC controllers' parameters on the control interactions. In the next section, we shall demonstrate an application example of this proposed interaction indicator in a multi-machine power system.

3. CONCLUSIONS

The major contributions of the paper are:

(1) For the first time as far as the authors are aware of, interactions between UPFC multiple control functions are analysed in terms of power system operation. It is concluded that the interactions are due to the control conflict of UPFC series and shunt part, which have internally electric connection, when active power regulation results in conflicting requirement in the connection.

(2) A simple interaction indicator is proposed which can be calculated from power flow solution without needing to design and install UPFC controllers.

APPENDIX

Data for SMIB installed with UPFC:

$H=4$, $D=10$, $T'_{do}=5.044$, $T'_{qo}=4$, $x_d=1.0$, $x_q=0.7$, $x'_d=0.3$, $r_a=0.01$, $K_A=2.0$, $T_A=0.02$

$x_E=0.3$, $x_B=0.03$, $C_{dc}=1$,

$x_1= x_2=j0.2$, $z_3=0.01+j0.4$, $z_4=0.01+j0.4$, $|V1|=1$, $V_2=1\angle 0$, $P_g=1.5$

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