**I. OBJECTIVE**

Implement Cooperative Distributed Control to a 100k node system model and produce real time results with the use of OPAL-RT real time simulator.

**II. EQUIPEMENT**

The list of equipment used for the experiment:

* OPAL-RT: the real-time simulator
* Simulink: the graphical programming environment developed by MATHWORKS
* OpenDSS: The Electric Power Distribution System Simulator
* Microsoft Excel

**III. IMPLEMENTATION**

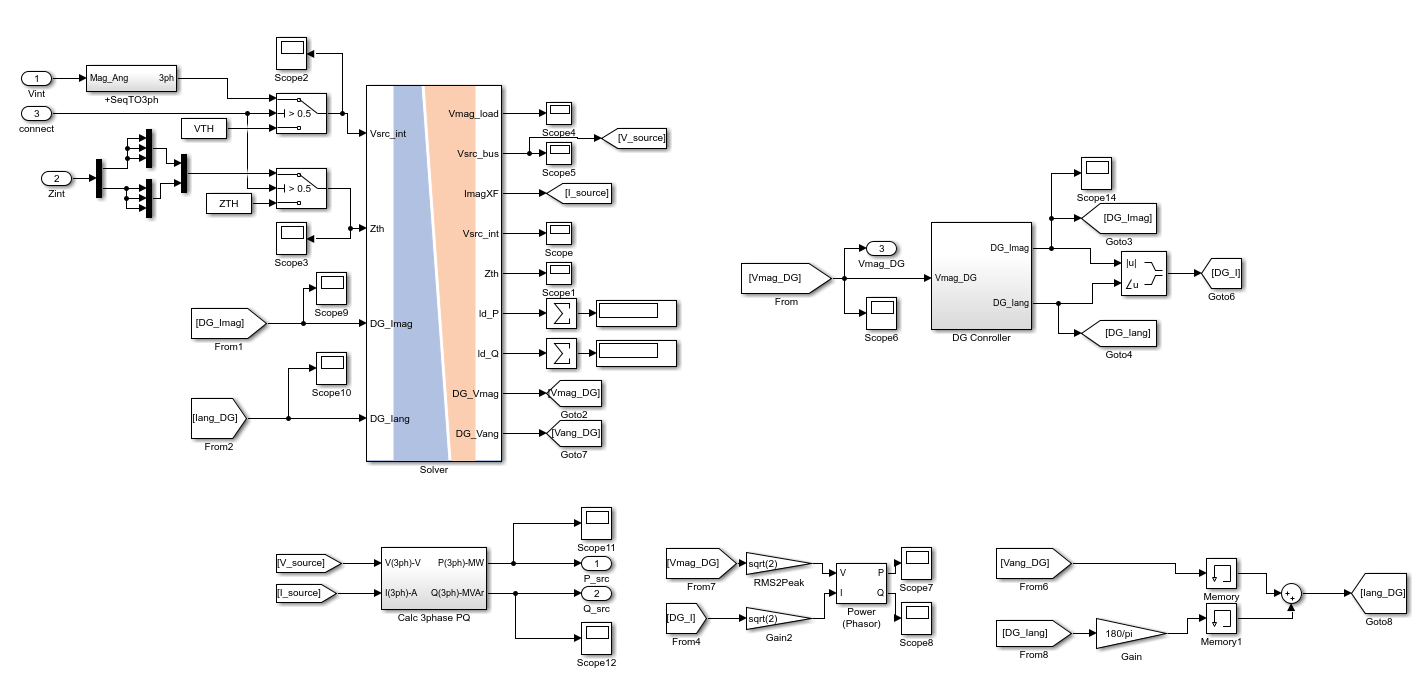
**Part 1: Implementation of the Cooperative Distributed Control to the T&D model**

The T&D model used for the implementation of the controllers was the same as described in the previous resport. IEEE 14-bus system was used as the transmission system and the IEEE European Low Voltage Test Feeder (ELV) as the distribution system. The T&D model connects forty ELV systems to one bus in the IEEE 14-bus system. This is done by sending the summation of the power measurement of all the ELV systems. As well as, substituting the ELV substation voltage source with the dynamic Thevenin equivalent of the transmission system, both the Thevenin voltage and the Thevenin impedance, seen at bus 11.

Bus 11 was chosen as the point of interconnection between the T&D due to it having the lowest load level of the system. This connection happens after 1.5 seconds of simulation where the Thevenin equivalents are initially calculated. IEEE 14-bus test case system was originally modeled in PSS/e and was kept this way when inputting the model to ePHASORsim solver block. The ELV was originally modeled in Excel and was kept this way when inputting the model to ePHASORsim solver block.

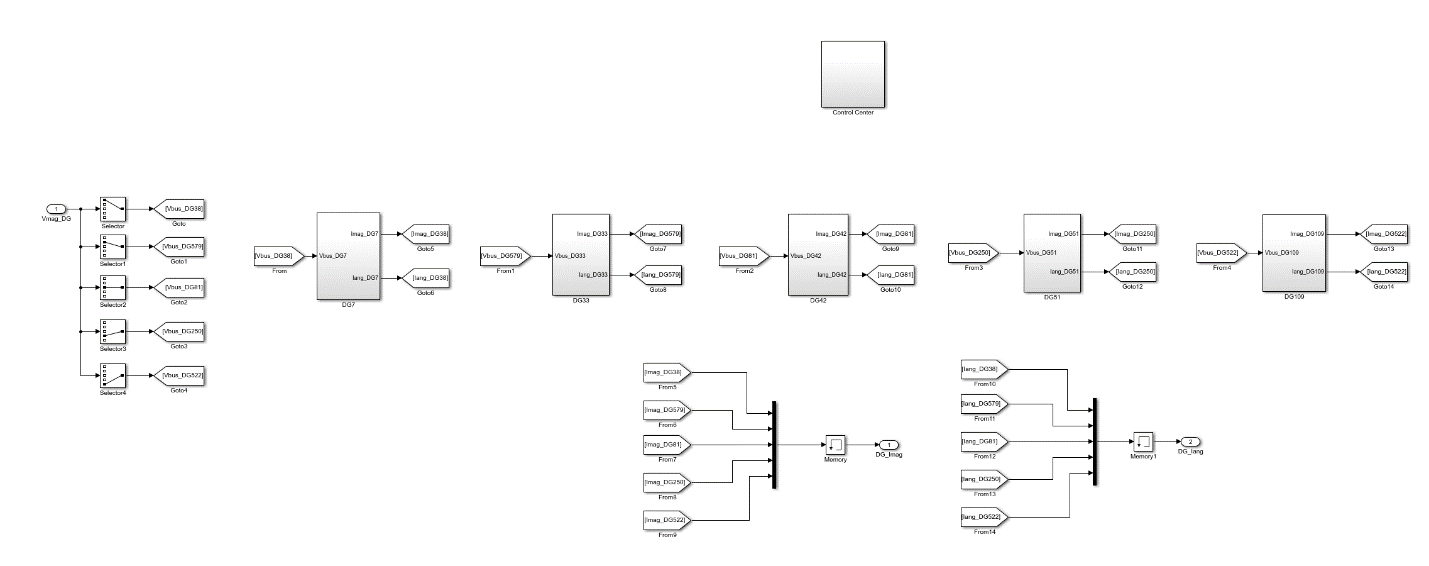
The Cooperative Distributed Control was modeled in Simulink. Five of which were connected to five buses in one of the ELV distribution system. More specifically, one controller per bus. In order for the cooperative control to work properly, it is required that each controller is placed to the same phase of the desired buses. The controllers were connected to phase A of bus 38, 81, 250, 522, and 579. As below in figure 1, the controllers take in the voltage magnitude and injects to the system the current magnitude and angle.

**Figure 1:** Implementation of Controller to one ELV system



DG Controller

The implemented Cooperative Distributed Controller is composed of a control center and five DGs, as shown below in figure 2. Each DG dynamically analyzes the voltage of the bus in which it is placed and injects current to it. It will then maintain the voltage within the specified threshold while supplying the power specified in the control center.

**Figure 2:** Inside DG Controller

Control Center

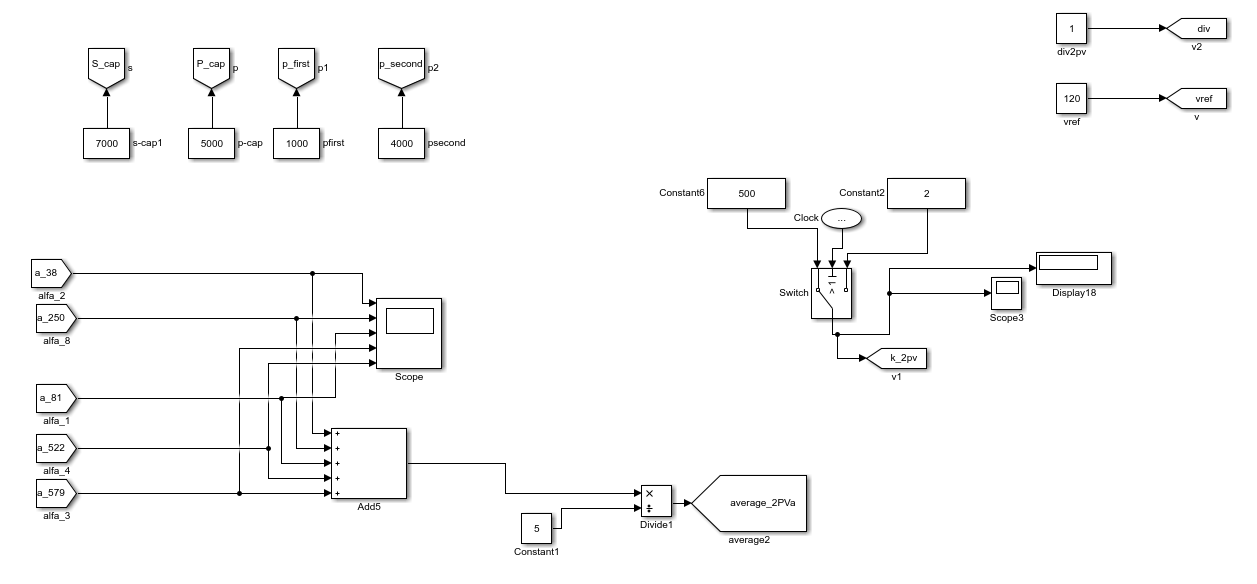
DG

**Part 2: Parameters of the controller**

As shown below in figure 3, inside the control center is where parameters for the DGs and ELV system are set. More specifically, the capacitance of the PV inverter (S\_cap), the maximum real power of the inverter (P\_cap), the initial power injection (P\_fisrt), second real power injection (P\_second), and the base voltage of the system (Vref).

Please refer to table 1, shown below, for the parameters used for the simulation. The initial power injection was set to 1 kW and the second power injection was set to 4kW. The second power injection will be applied after 3 seconds of simulation. The voltage reference was set to 120V line-to-neutral, which is the base voltage of the ELV system. In addition, it is very important to note that the voltage threshold for the control was set to 6, or 5% of Vref.

**Figure 3:** Control Center

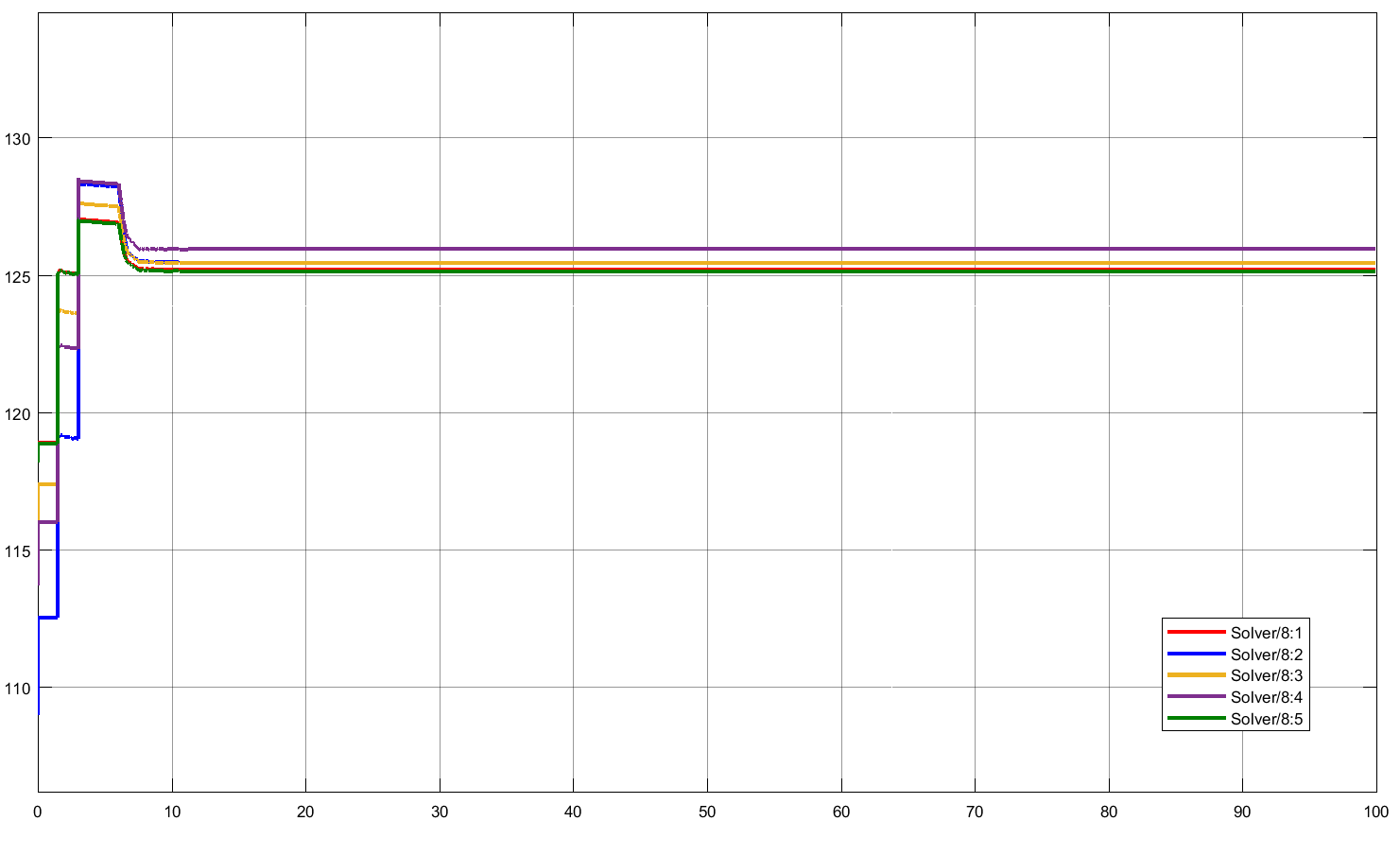


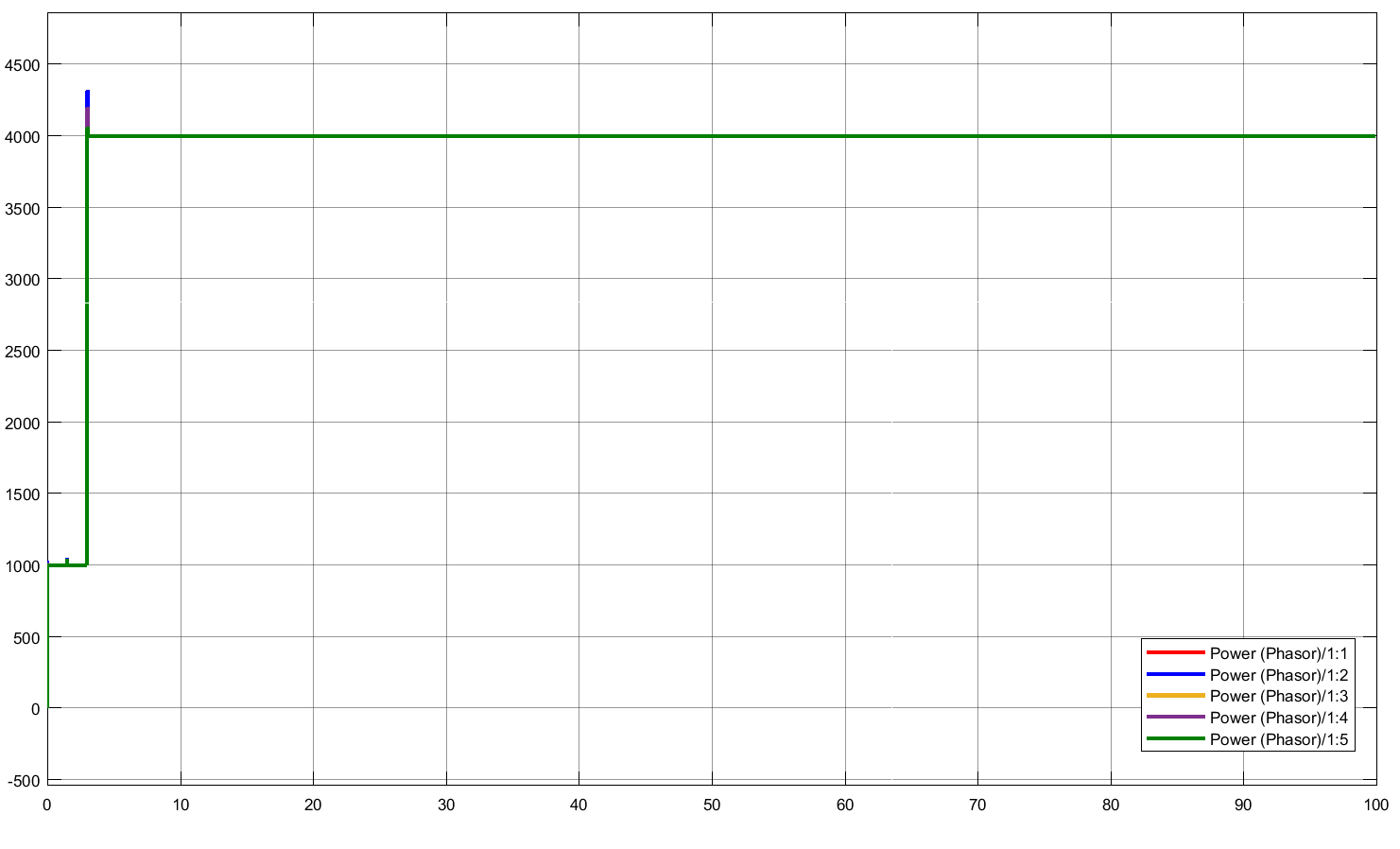
**Table 1:** Control Center Parameters

|  |  |
| --- | --- |
| **S\_Cap** | 7000 VA |
| **P\_cap** | 5000 W |
| **P\_first** | 1000 W |
| **P\_second** | 4000 W |
| **Vref** | 120 V |

**Part 3: Results**

As shown below in figure 4, the controller was able to inject the specified power while maintaining the voltage within the specified threshold of 6. It is important to note that the legend shown below in table 2 applies for figures 4, and 5. Figure 5, proves that the controllers injected 1kWat the start of the simulation and 4kW after after 3 seconds.

**Figure 4:** Voltage Magnitude of buses with Controllers

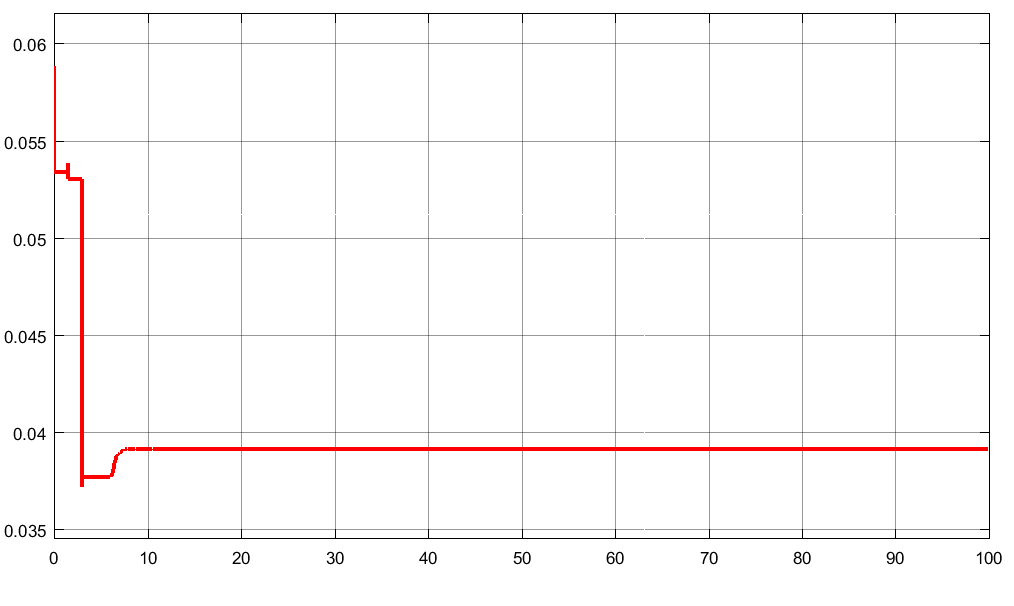
**Figure 5:** Power injection

**Table 2:** Legend for figures 4, and 5

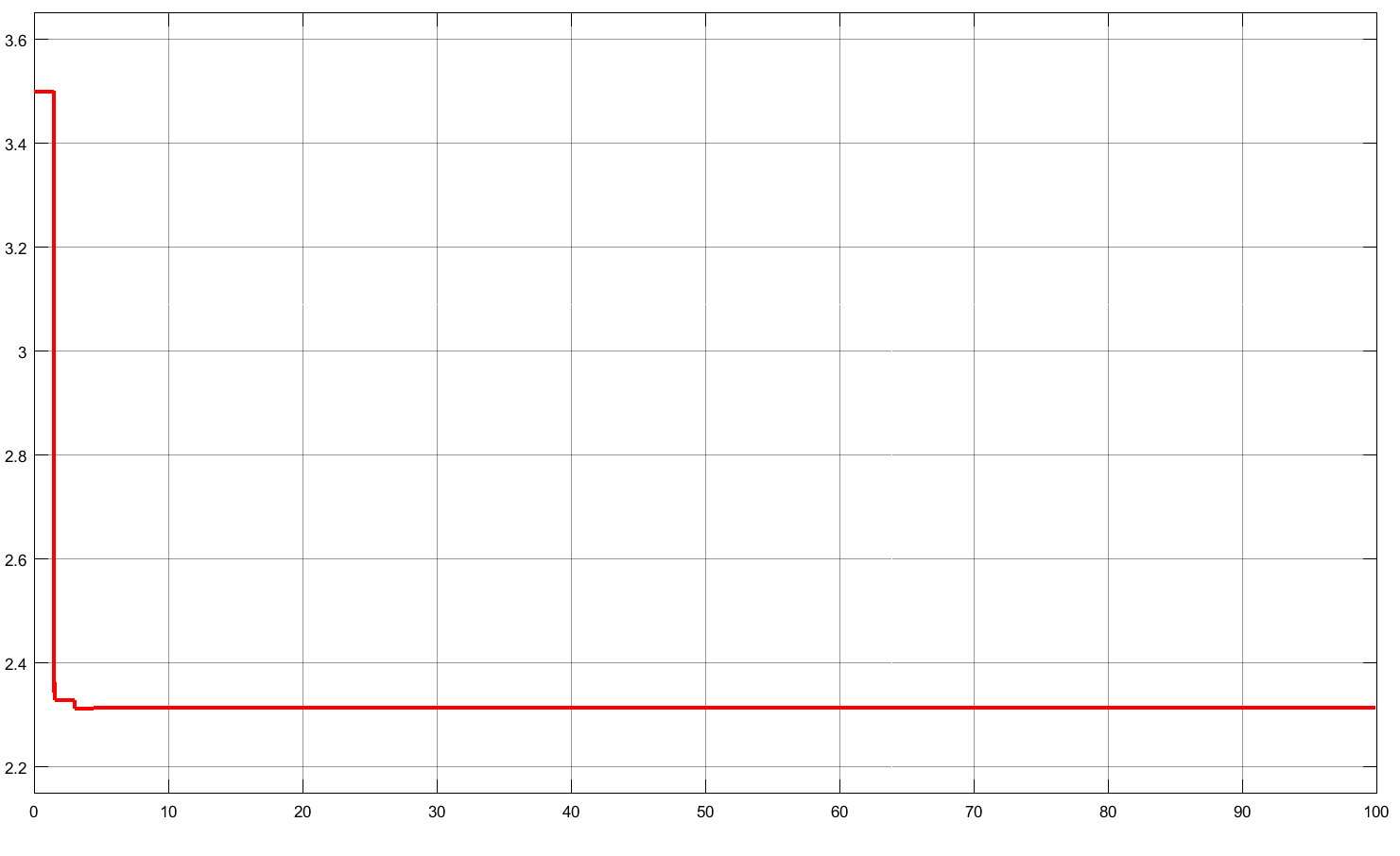
|  |  |
| --- | --- |
|  | **ELV - Bus #** |
| **Red** | 38 |
| **Blue** | 579 |
| **Orange** | 81 |
| **Purple** | 250 |
| **Green** | 522 |

Figure 6 demonstrates the real power injection change at the source bus of the ELV system to which the controllers are connected to. The load starts at 58.9kW and it converges to 39.2kW. It demonstrates how the system’s real power load goes down by 19.7kW after the system converges. This is as expected since each of the 5 DGs inject 4kW of power to the ELV system. Figure 7 shows the total real power injection of the forty ELV systems to bus 11 of IEE 14-bus transmission system. It portrays how the load goes down after the 3 seconds of simulation were the DGs make their second power injection. Figure 8 shows how the per unit voltage at bus 11 of IEEE 14-bus system converges to a little over 1.059.

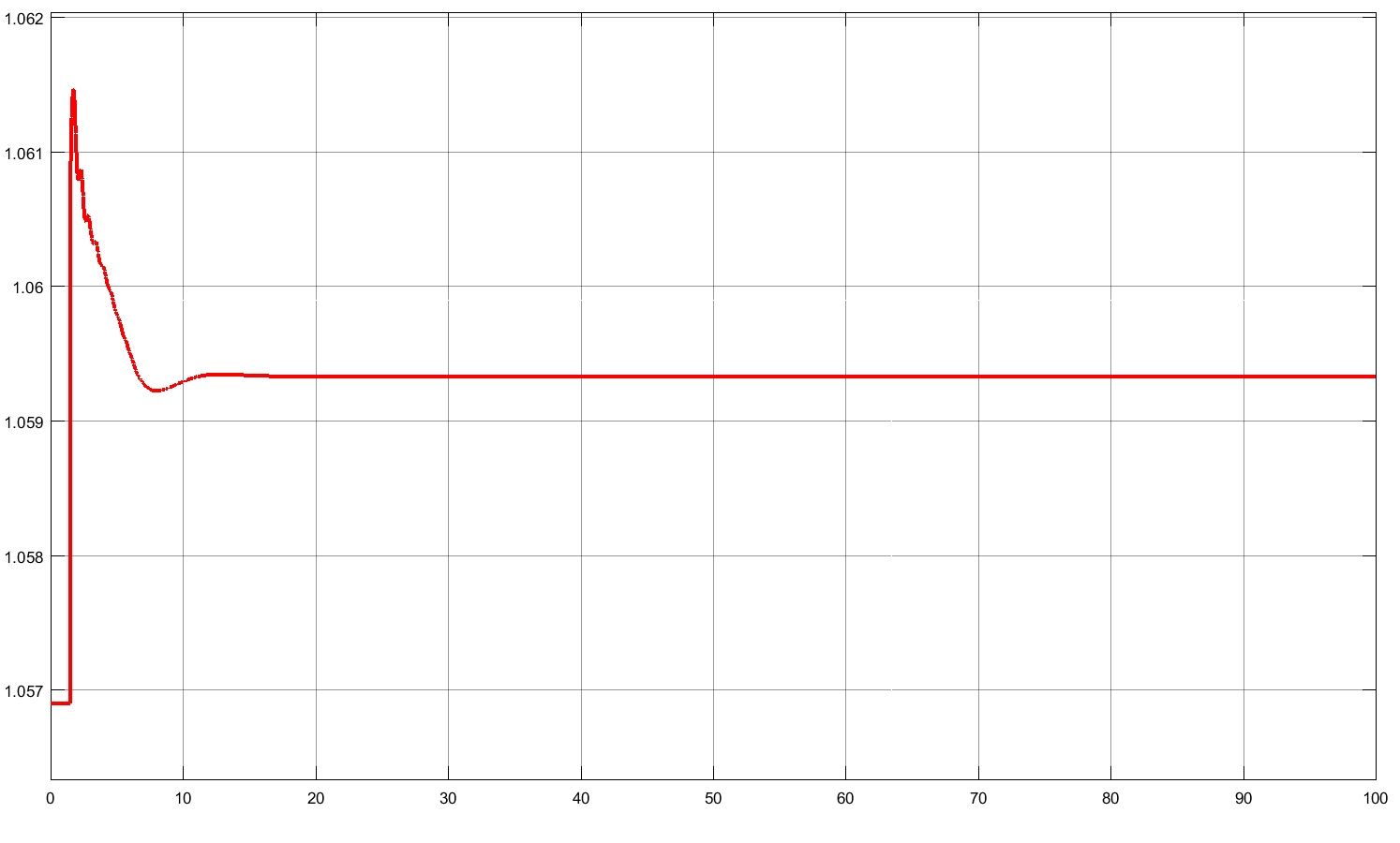
**Figure 6:** Real Power at the source bus of the ELV system



**Figure 7:** Real Power injection to bus 11 of IEEE 14-bus system



**Figure 8:** Per Unit Voltage at bus 11 of IEEE 14-bus system



The T&D model developed and utilized to perform the mentioned simulations, was developed in OpenDSS in order to compare the results. It was seen that the results were similar and the voltages of the buses which had a controller connected to it is shown below in figure 9.

**Figure 9:** OPAL-RT vs OpenDSS

**IV. Conclusion**

Results were as expected. The controllers were able to inject the power specified in the control center while maintain the voltages of the bus, at which they are connected to, within the specified voltage threshold. The result comparison with OpenDSS further confirms results.