Equivalent modelling of several PV power plants

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I. Introduction:

The main objective of this study and report is making an equivalent model of several PV power plants connected to a grid and, along with it, investigating the probability of reactive power counteractions among PV plants that might not be seen and addressed in the equivalent model. Therefore the work that has been done so far is bulleted as follows:

- Studying and inspecting the final model that was developed by [1]
- Making the template of the aforementioned model in PowerFactory to make integration of duplicated models easily
- Making equivalent of the PV plant model by scaling up the current model
- Running different scenarios

II. PV System Model in PowerFactory

The employed PV model in PowerFactory in this research consists of PV array model, Maximum Power Point Tracking (MPPT), dc-bus capacitor, static generator and peripheral control systems. The PV model is also associated with a voltage control regulator as Fig. 1, where $F_{vac}(s)$ can, in general, be a PI controller. $F_{vac}(s)$ adjusts reactive power in such a way to regulate the voltage.

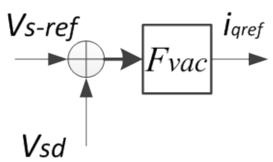


Fig.1 Block diagram of the voltage control in the PV model.

III. Equivalent Model

Since the equivalent (aggregated) model is supposed to be connected to the same voltage level as individual PV systems in the non-aggregated model, only the power level of the current PV model should be manipulated to make the equivalent model. In other words, the dc-link voltage remains similar in the both equivalent PV model and individual PV systems in non-aggregated model. In order to change the power level, the number of the parallel solar panels must be changed. Furthermore, considering identical voltage level and the following power equation across the dc-link capacitor, it is clear that the capacitor size must be also multiplied by the number of individual PV systems in the equivalent.

$$\frac{1}{2}C\frac{dv_{dc}^2}{dt} \simeq P_{dc} - P_{ac}$$

The power rating of the equivalent transformer for the equivalent model is calculated based on the number of individual PV systems in the equivalent model and the transformer rating of one individual PV system. In PowerFactory the transformer impedance is indicated in per-unit. Therefore via increasing the rating power of the transformer by the factor of the number of individual PV systems, the impedance of the equivalent transformer decreases by the same factor, which is in conjunction with the Thevenin impedance of the parallel transformers in case of individual PV systems.

IV. Case Study

It is assumed that three individual PV systems are connected through three transformers to the medium voltage bus-bar (MV-A) and, in turn, through a line to the Thevenin model of the grid, it is shown on the right hand side of Fig. 2. As can be also seen on the left hand side of Fig. 2, the equivalent of these three PV systems has been built and incorporated into the same simulation framework, and it is connected through the equivalent transformer to a medium voltage bus (MV-B) and, in turn, through the same identical line to the Thevenin model of the grid. Nominal power of non-aggregated PV model is 450 kW. The gird and PV data has been given in Table I.

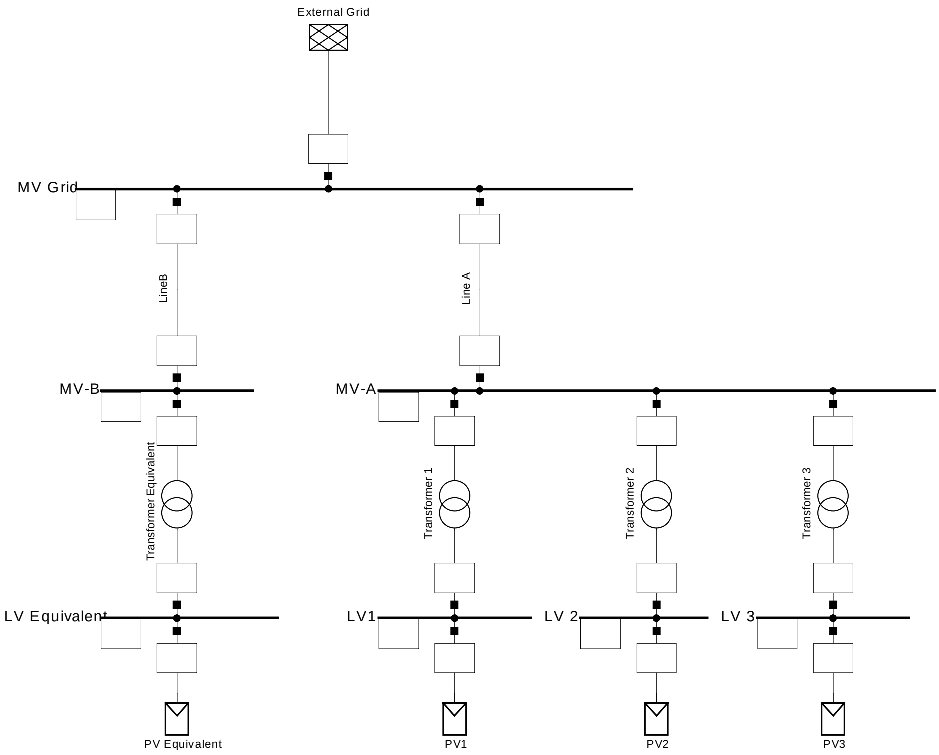


Fig. 2: Schematic of the case study grid

Table I: The grid and PV system data are

PV Panel Parameters	Maximum Current Imp	Maximum Voltage Imp	Short Circuit Current Isc	Short Circuit Voltage Vsc
	3.56A	33.7 V	3.87	42.1 A
Non-Aggregated Transformer Parameter	Nominal Power	Voltage ratio and type	Short Circuit voltage, u_k	Resistive Short Circuit voltage, u_{kr}
	560 kVA	10/0.4 kV, Dyn11	4%	2%
Equivalent Transformer Parameters	Nominal Power	Voltage ratio	Short Circuit voltage, u_k	Resistive Short Circuit voltage, u_{kr}
	1.89 MVA	10/0.4 kV, Dyn11	4%	2%
Line parameters	Rated Voltage	Rated Current	Resistance	Reactance
	15 kV	355A	2.5Ω	5Ω

V. Simulation Results

For simplicity, irradiance is varied step-wise. In order to consider and address all the aspects, possible scenarios are studied. The following assumptions are similar in all scenarios:

- All PV systems are associated with MPPT.
- All PV systems are associated with the voltage controller.
- The voltage controller is a pure integrator (I).

A. Scenario 1

In this scenario following assumptions are considered:

- Irradiance level is varied identically for all PV systems in the non-aggregated model.
- In the non-aggregated model, all individual transformers are identical.
- Voltage controller parameters are identical.
- PV systems are supposed to regulate the voltage at the LV bus.
- The voltage set-point is adjusted to 1.01 p.u.

Fig. 3 shows that the irradiance initially is $1000\ W/m^2$ for both PV models and then at $t=1.5\ s$ the irradiance is changed identically to $500\ W/m^2$ for both PV models.

As can be seen in the Fig. 4, the total injected active powers are same in the both non-aggregated and aggregated model. The dc-link voltages for PV systems in both models have been shown in Fig. 5, and as expected, they are identical which boils down to identical irradiance variations. As Fig. 6 depicts, the total contributed reactive powers to regulate the voltage to the set-point are also same. In other words, there is no counteraction among individual PV systems in non-aggregated model, and aggregated model is, therefore, a correct representative of the aggregation. Fig. 7 (a) illustrates that LV-bus voltages, in non-aggregated and aggregated model, have been kept constant and are identical in both models. Fig. 7 (b) also shows MV-bus voltages for both models, and as can be seen MV-bus voltages are also similar in both models.

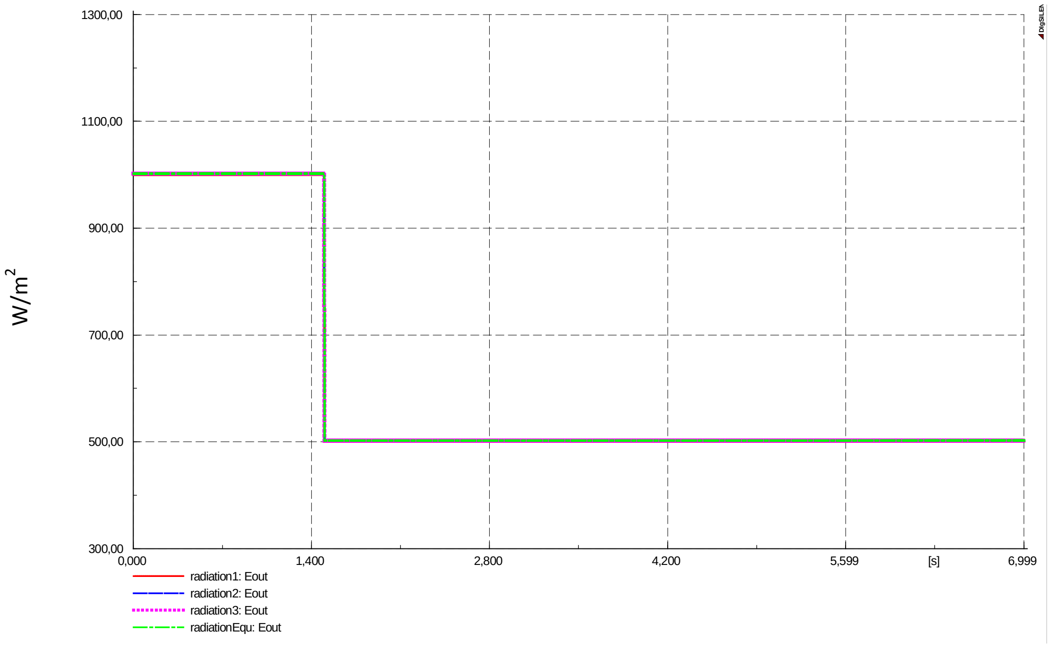


Fig.3: Irradiance variation in Scenario 1

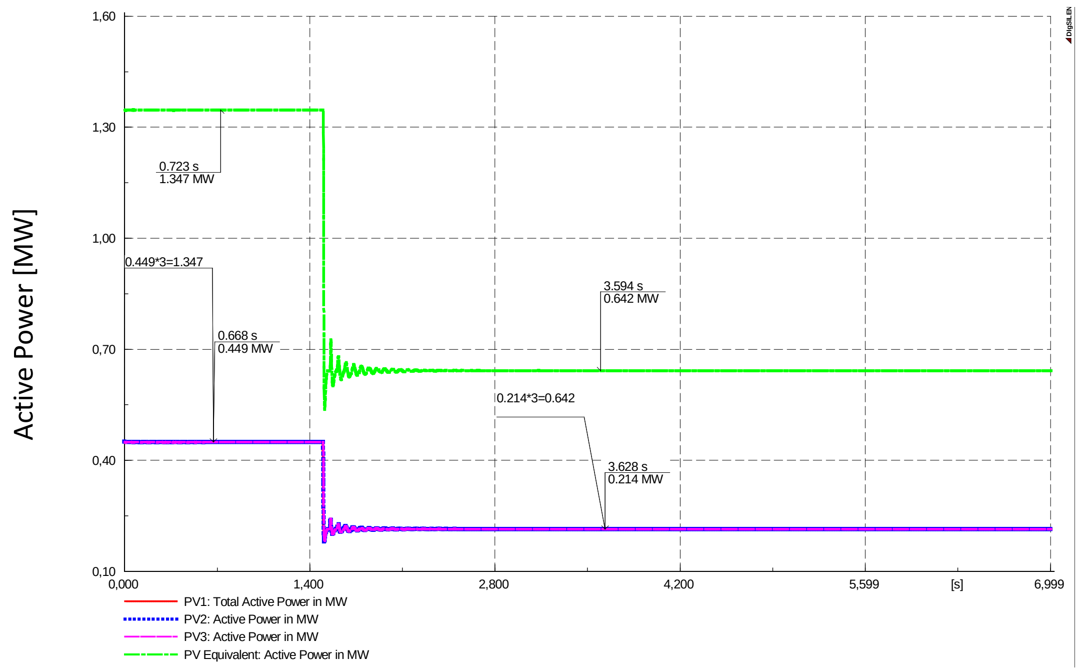


Fig.4: Total active power in scenario 1

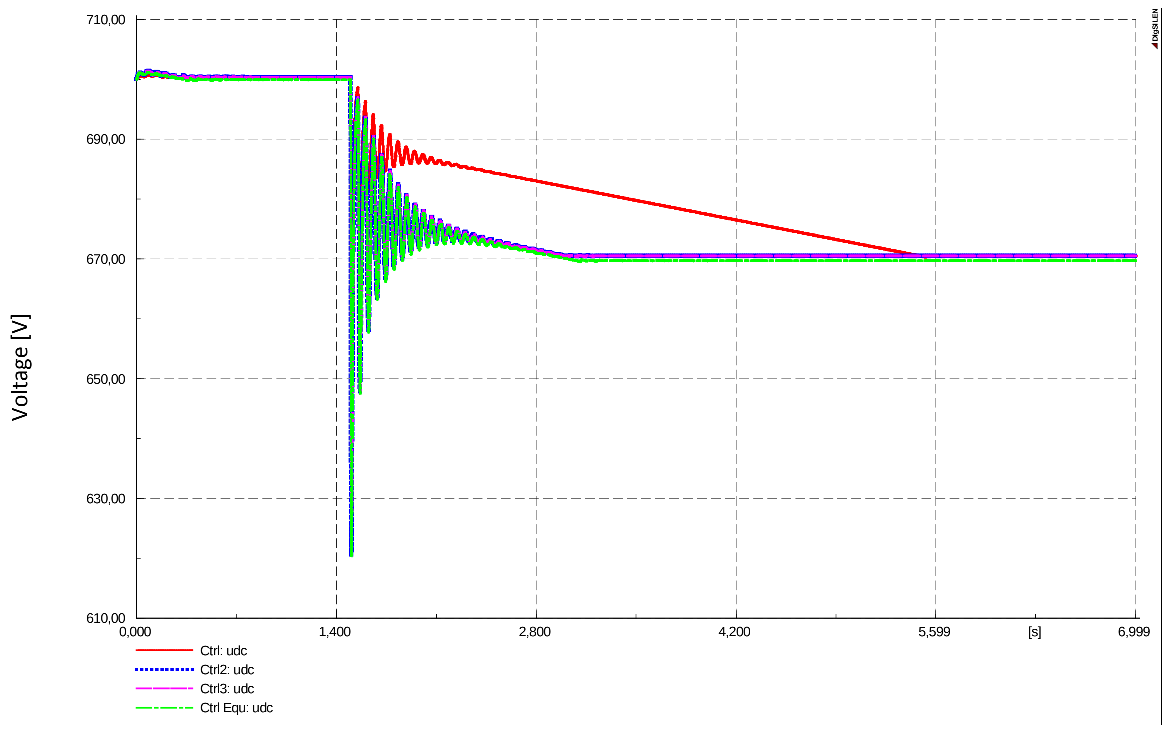


Fig.5: dc-link voltages in scenario 1

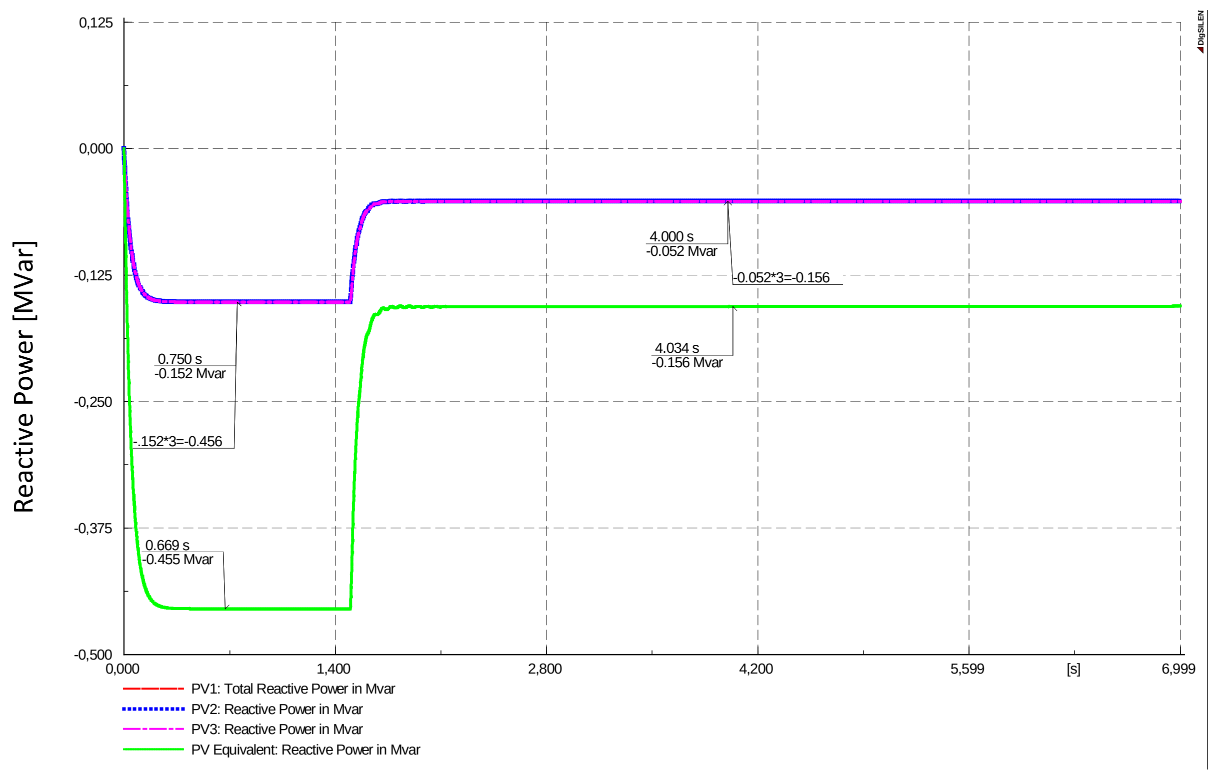
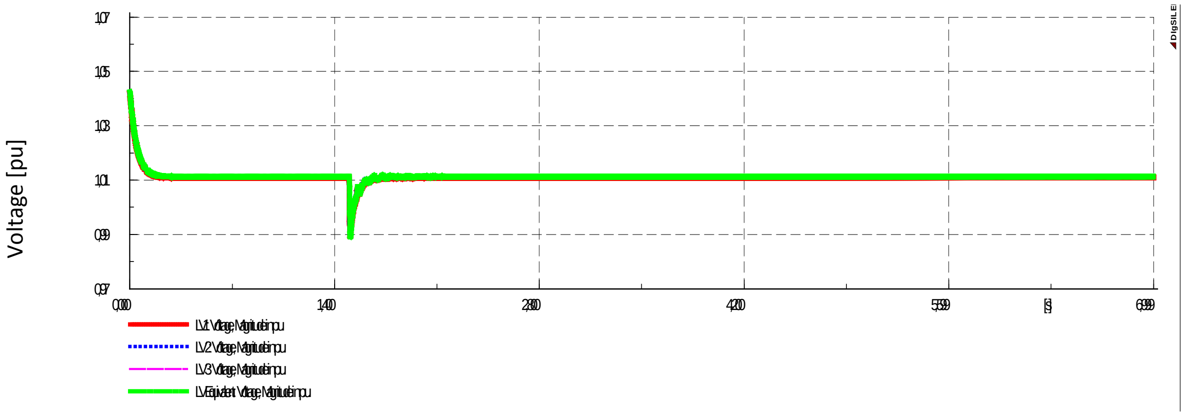
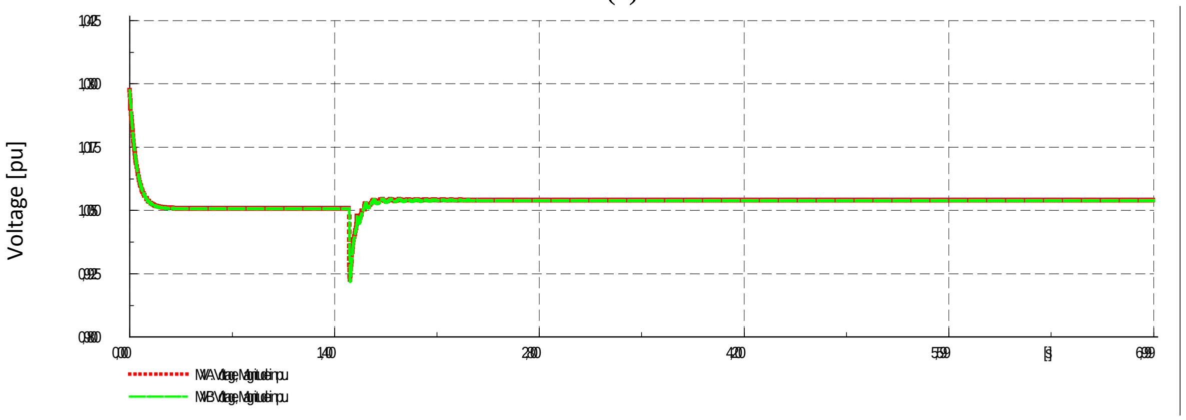


Fig.6: Total reactive powers in scenario 1



(a)



(b)

Fig. 7: AC voltages in scenario 1: (a) LV buses. (b) MV buses.

B. Scenario 2

In this scenario following assumptions are considered:

- Irradiance level is varied differently for PV systems in the non-aggregated model.
- In the non-aggregated model, all individual transformers are identical.
- Voltage controller parameters are identical.
- PV systems are supposed to regulate the voltage at the LV bus.
- The voltage set-point is adjusted to 1.01 p.u.

In contrast to scenario 1, in this scenario the variability of the irradiance among individual PV systems is also taken into account. In other words, it is assumed that individual PV systems in non-aggregated model are exposed to the different irradiance. Furthermore, the irradiance of the aggregated model is assumed to be the mean value of irradiance levels of individual PV systems in non-aggregated model. As Fig. 8 shows, the irradiance initially is $1000\ W/m^2$ and it is varied at $t=1.5\ s$ to *500*, *400* and $300\ W/m^2$ for PV1, PV2 and PV3 in non-aggregated model, respectively, and, in turn, the irradiance of aggregated model (PV Equ) is varied to $400\ W/m^2$.

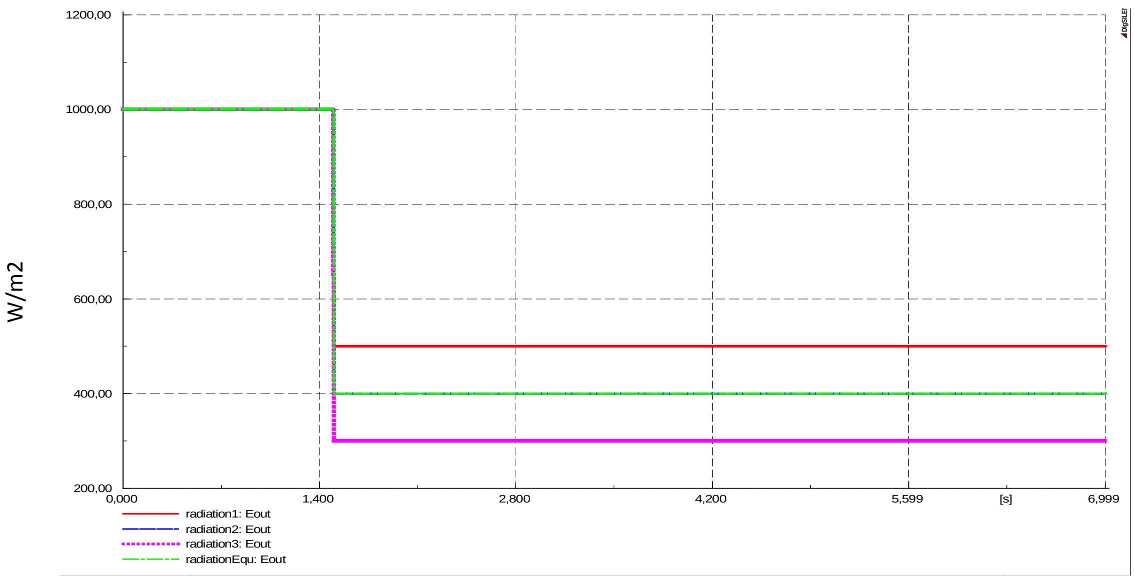


Fig. 8: Irradiance variation in Scenario 2

As can be seen in the Fig. 9, similar to scenario 1, the total injected active powers are same in the both non-aggregated and aggregated model. The dc-link voltages for PV systems in both models have been shown in Fig. 10, they are identical before *t=1.5 s* and afterwards they settle down in conjunction with the related irradiance and since the PV2 in the non-aggregated model and the aggregated PV model are exposed to the same irradiance, their steady-state voltages are same.

As Fig. 11 depicts, the total contributed reactive powers to regulate voltage to the set-point are also same in both models (*=-0.026 Mvar*). Nevertheless, it is obvious that the reactive power of PV3 is on the edge towards capacitive; therefore, in scenario 3 another irradiance variation will be addressed to investigate more. Fig. 12 (a) illustrates that LV-bus voltages in non-aggregated and aggregated model have been kept constant and are identical in both models. Fig. 12 (b) also shows MV-bus voltages for both models, and as can be seen MV-bus voltages are also similar in both models.

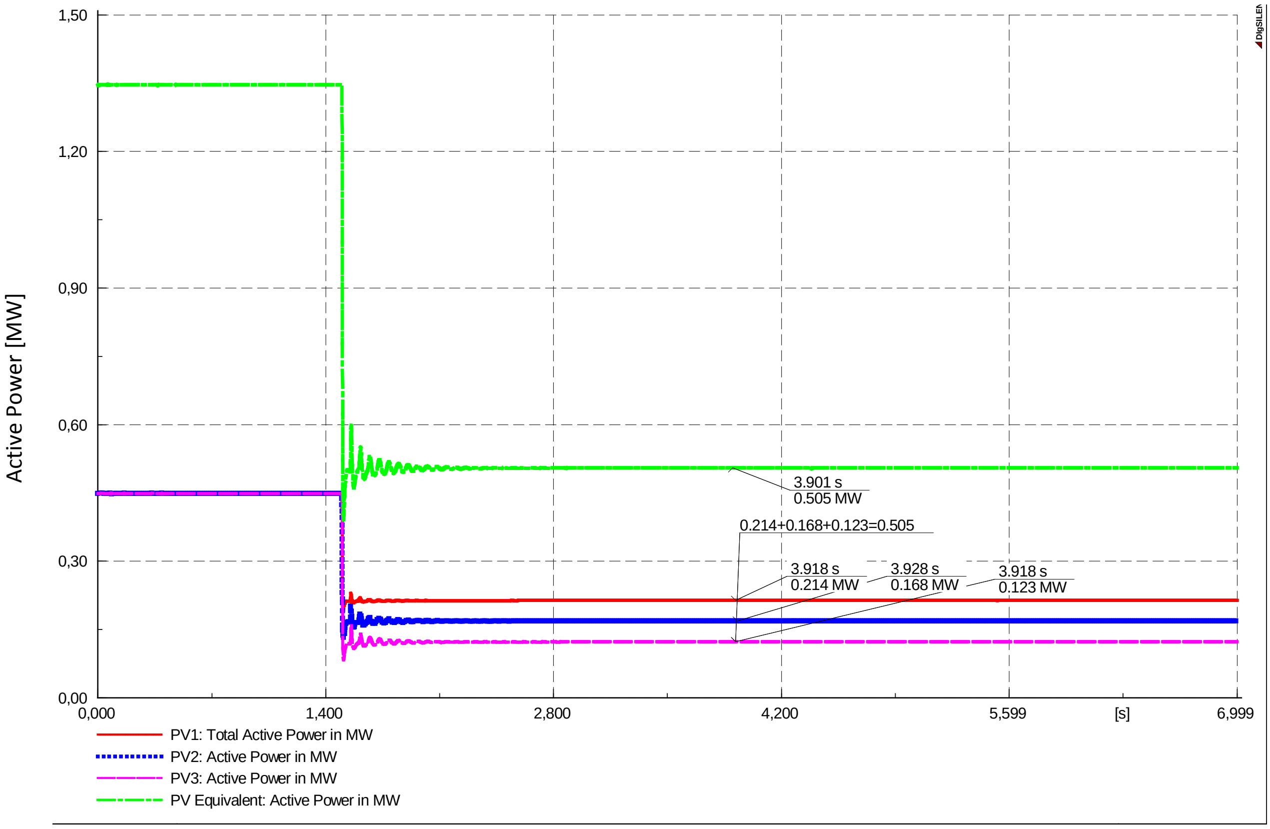


Fig. 9: Total active power in scenario 2

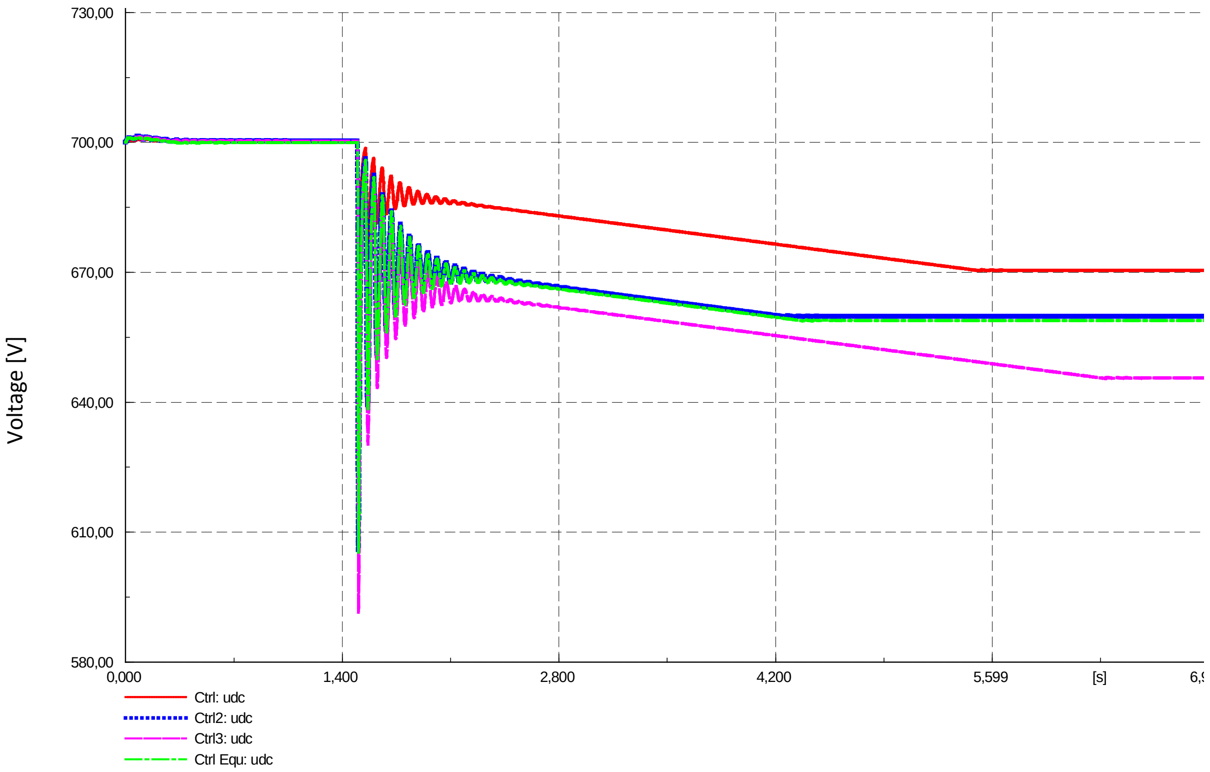


Fig. 10: dc-link voltages in scenario 2

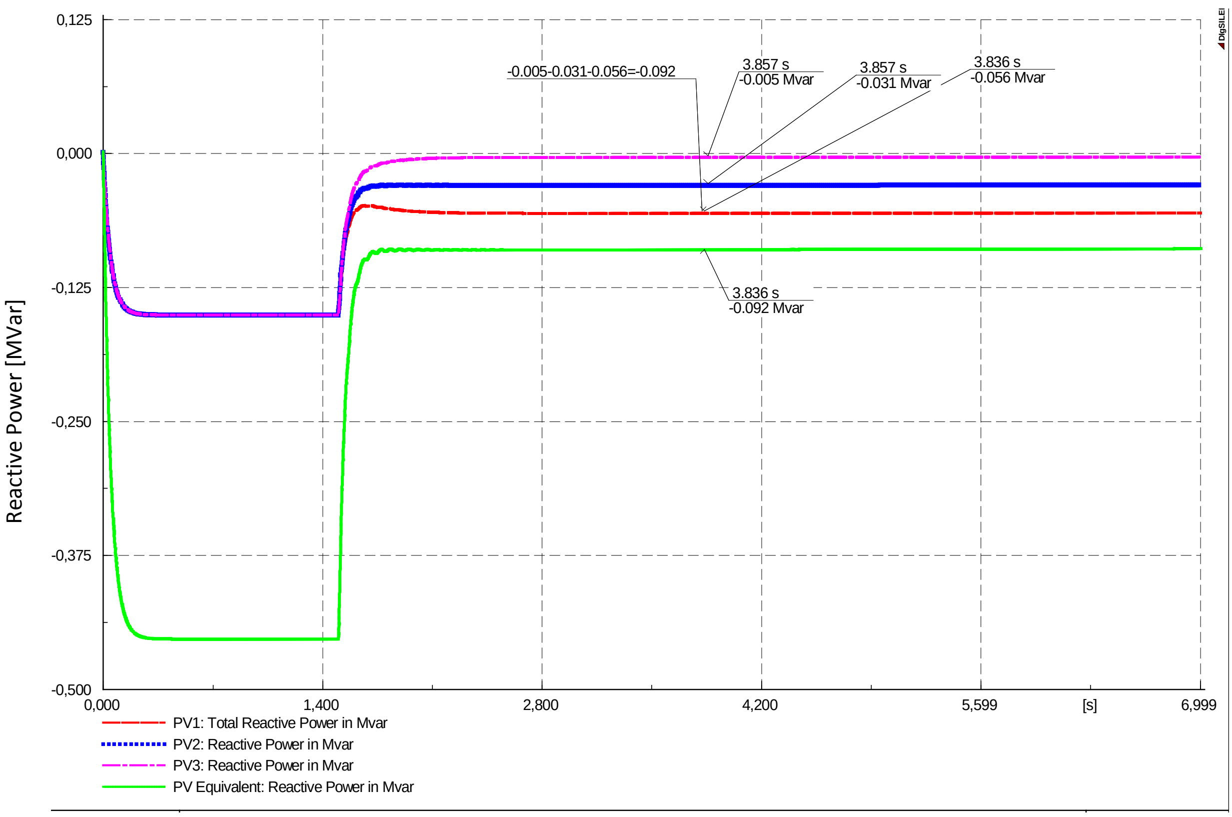
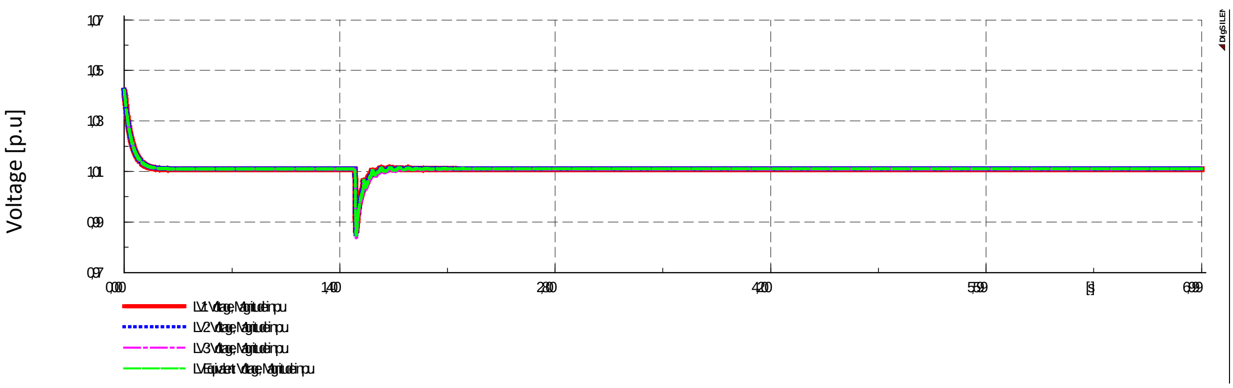
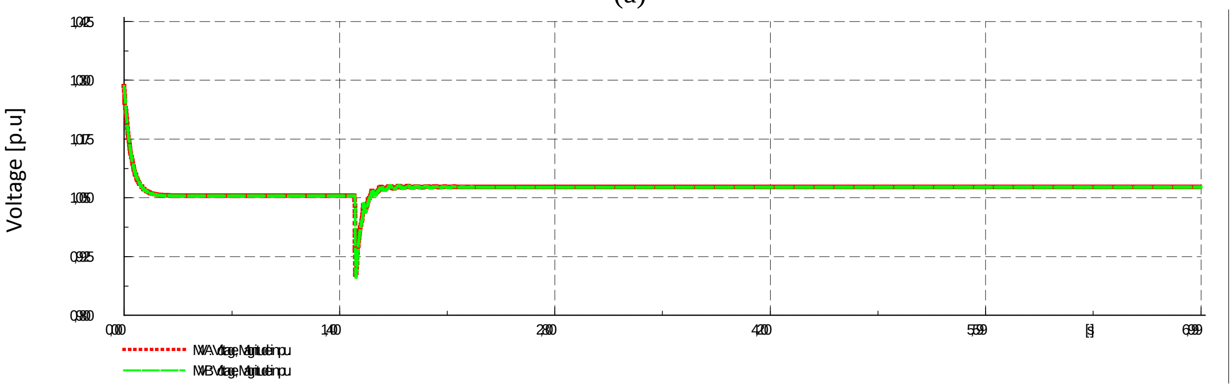


Fig. 11: Total reactive powers in scenario 2



(a)



(b)

Fig. 12: AC voltages in scenario 2: (a) LV buses. (b) lower figure) MV buses

C. Scenario 3

In this scenario following assumptions are considered:

- Irradiance level is varied differently for PV systems in the non-aggregated model.
- In the non-aggregated model, all individual transformers are identical.
- Voltage controller parameters are identical.
- PV systems are supposed to regulate the voltage at the LV bus.
- The voltage set-point is adjusted to 1.01 p.u.

This scenario except the irradiance variation scheme is similar to scenario 2. In scenario 3 the irradiance is changed as Fig. 12.

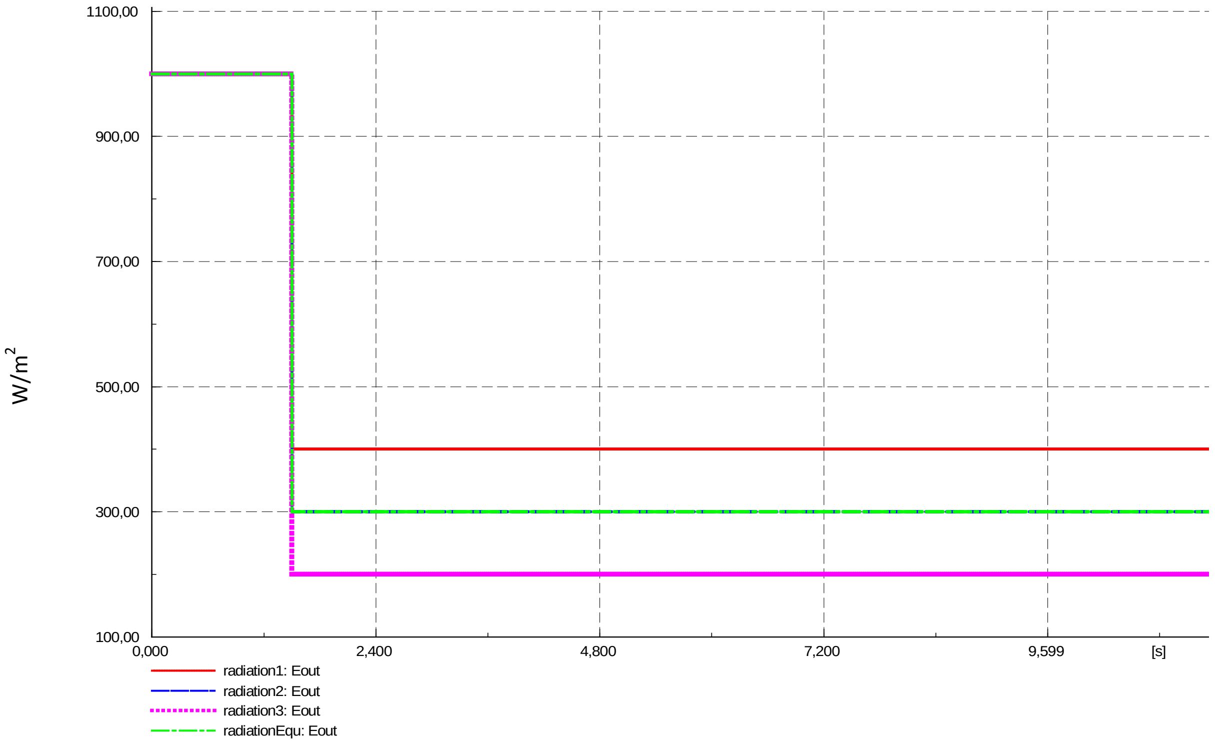


Fig. 13: Irradiance variation in Scenario 3

Concerning the active power, the summation of individual active power of each non-aggregated PV models is equal to 0.370 MW that is analogous to aggregated model (Fig. 14). Fig. 15 shows that dc-link voltages.

Regarding the reactive power, Fig. 16, it is obvious that in non-aggregated model, PV3 works in capacitive mode while PV1 and PV 2 work in inductive mode. Nevertheless, the total reactive power in non-aggregated model is equal to the aggregated model (=*-0.026 Mvar*). Furthermore, as can be seen in Fig. 17 (a), LV-bus voltages are also regulated to the set-point properly. Therefore, even though the PV systems in non-aggregated model are working in different modes (inductive and capacitive), it has no negative effect on the voltage regulator performance.

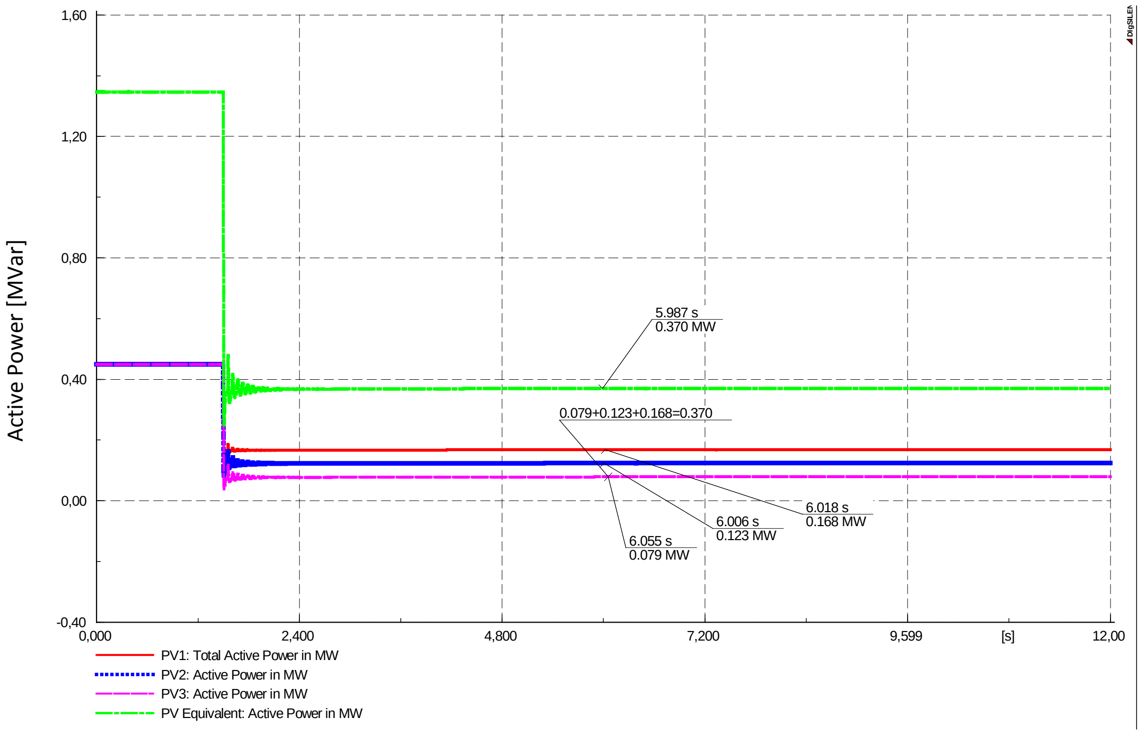


Fig. 14: Total active power in scenario 3

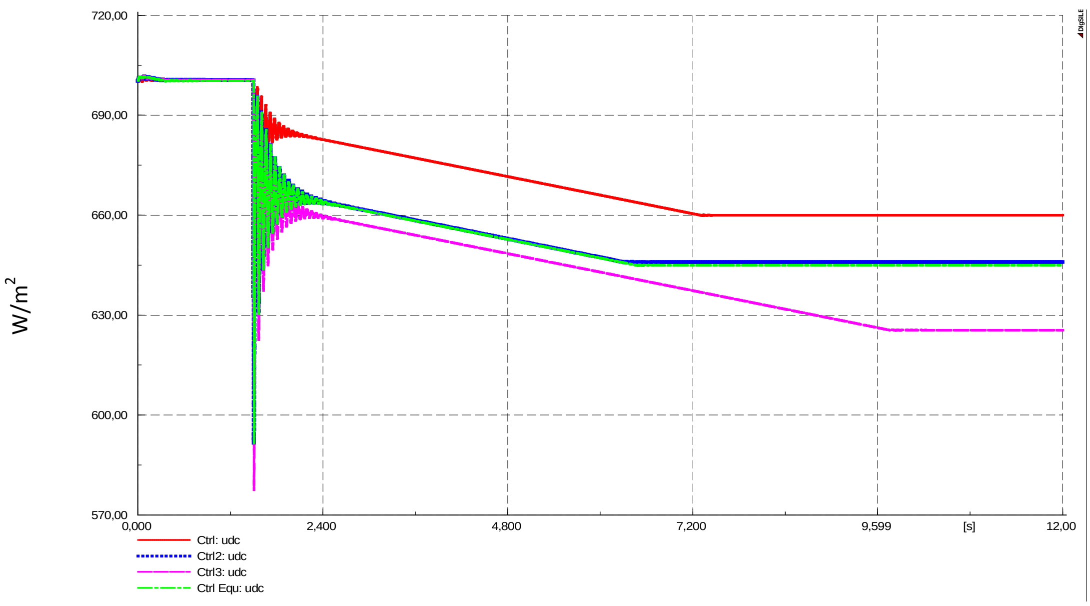


Fig. 15: dc-link voltages in scenario 3

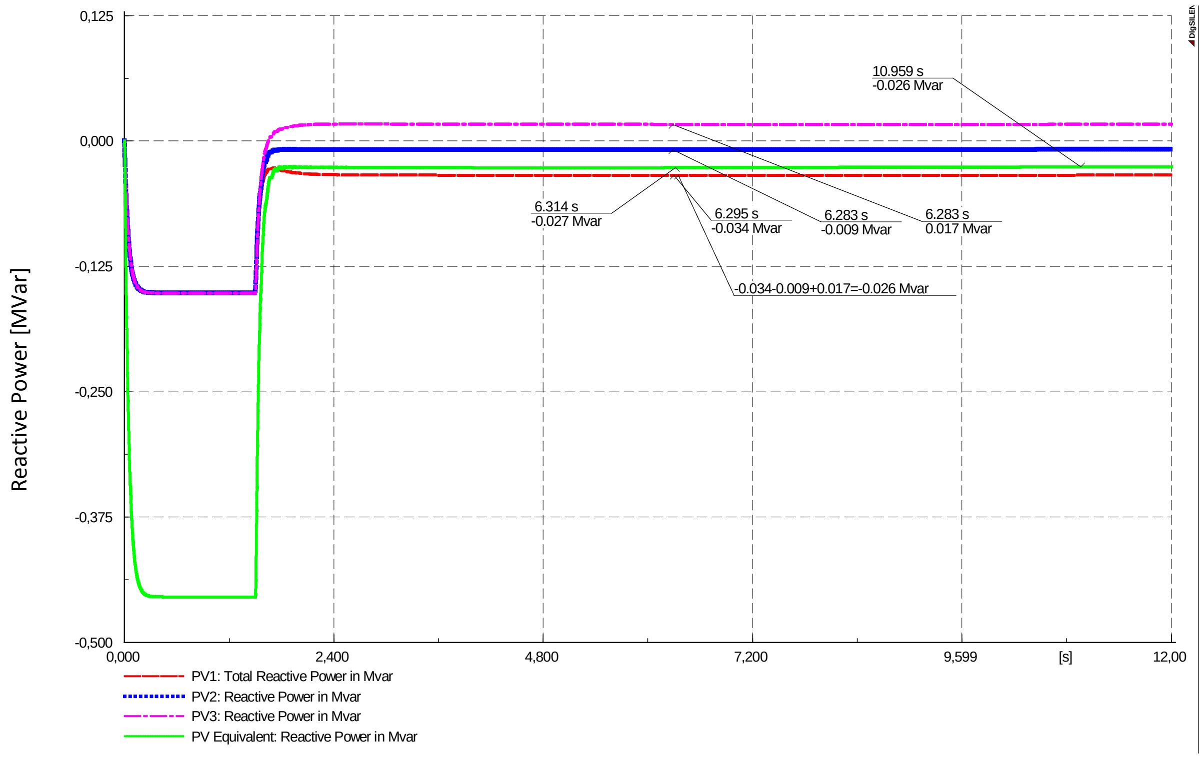
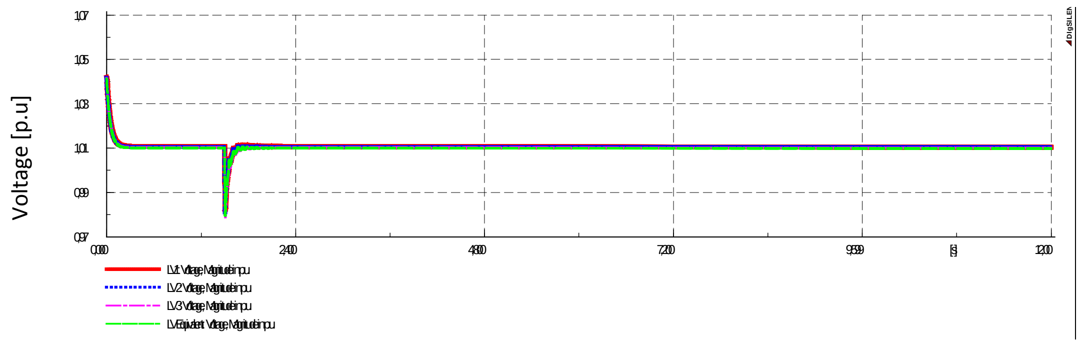
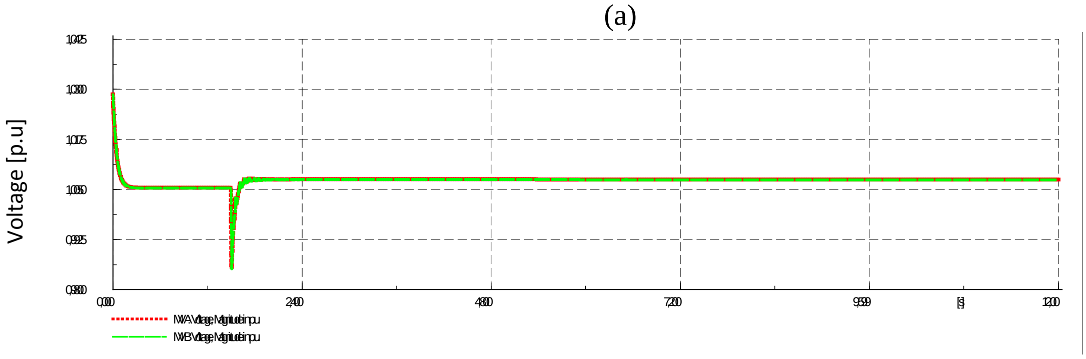


Fig. 16: Total reactive powers in scenario 3



(a)



(b)

Fig. 17: AC voltages in scenario 3. (a) LV buses. (b) MV buses.

D. Scenario 4

In this scenario following assumptions are considered:

- Irradiance level is varied differently for PV systems in the non-aggregated model.

- In the non-aggregated model, individual transformers are different.
- Voltage controller parameters are identical.
- PV systems are supposed to regulate the voltage at the LV bus.
- The voltage set-point is adjusted to 1.01 p.u.

In contrast to scenario 3, in this scenario is assumed that individual transformers in non-aggregated model are not identical anymore. Therefore, the rating power of transformer 2 and 3 is decreased by 10%. The results show that the main difference is in the reactive power. Fig. 18 shows total reactive powers in both models. Before *t=1.5 s* all PV systems are working in inductive mode and the total reactive power of the non-aggregated model is equal to *(-0.143×2-0.159=) -0.445 Mvar* while the total reactive power of the aggregated model is *-0.455 Mvar*. Therefore, there is *0.01 Mvar* difference between non-aggregated and aggregated model. It can be seen from Fig. 18 that by changing irradiance at *t=1.5 s*, PV2 and PV3 start working in capacitive mode while PV1 functions in inductive mode. Therefore, compared to scenario 3 the operation mode of the PV2 has changed. Moreover, the total reactive power of the non-aggregated model and aggregated model settle down at *(-0.045+0.001+0.026=)-0.018 Mvar* and *-0.026 Mvar*, respectively. Therefore, the difference between reactive power of non-aggregated model and aggregated model is *0.008 Mvar*. Fig. 19 shows LV-bus and MV-bus voltages, it can be seen that LV-bus voltages are regulated to the set-point. Therefore, one can draw this conclusion that there is no counteraction between controllers on the grounds that irrespective of different operation modes (capacitive or inductive) among individual PV systems and different total reactive powers between aggregated and non-aggregated model, the voltage regulation is fulfilled satisfactory. Moreover, compared to scenario 3, one can also conclude that the total reactive power deviation is due to non-uniformity of individual transformers in non-aggregated model.

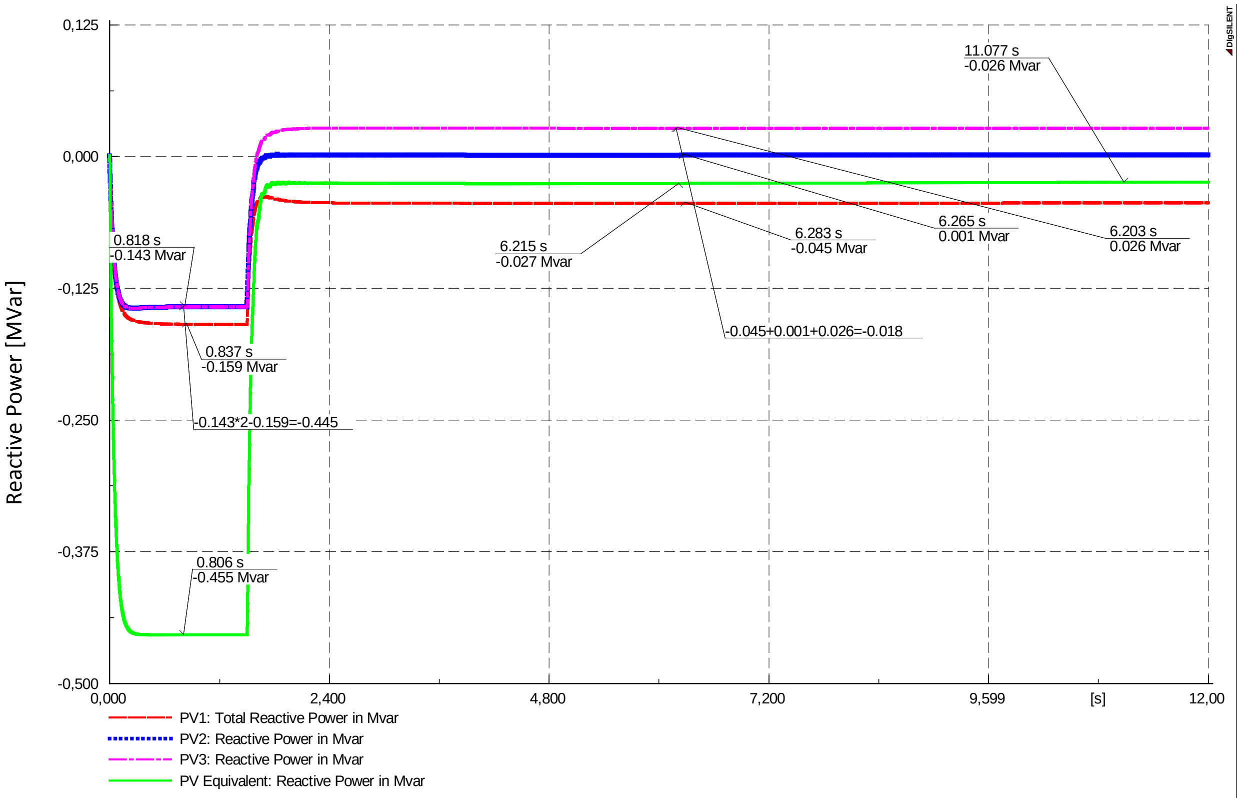


Fig. 18: Total reactive powers in scenario 4

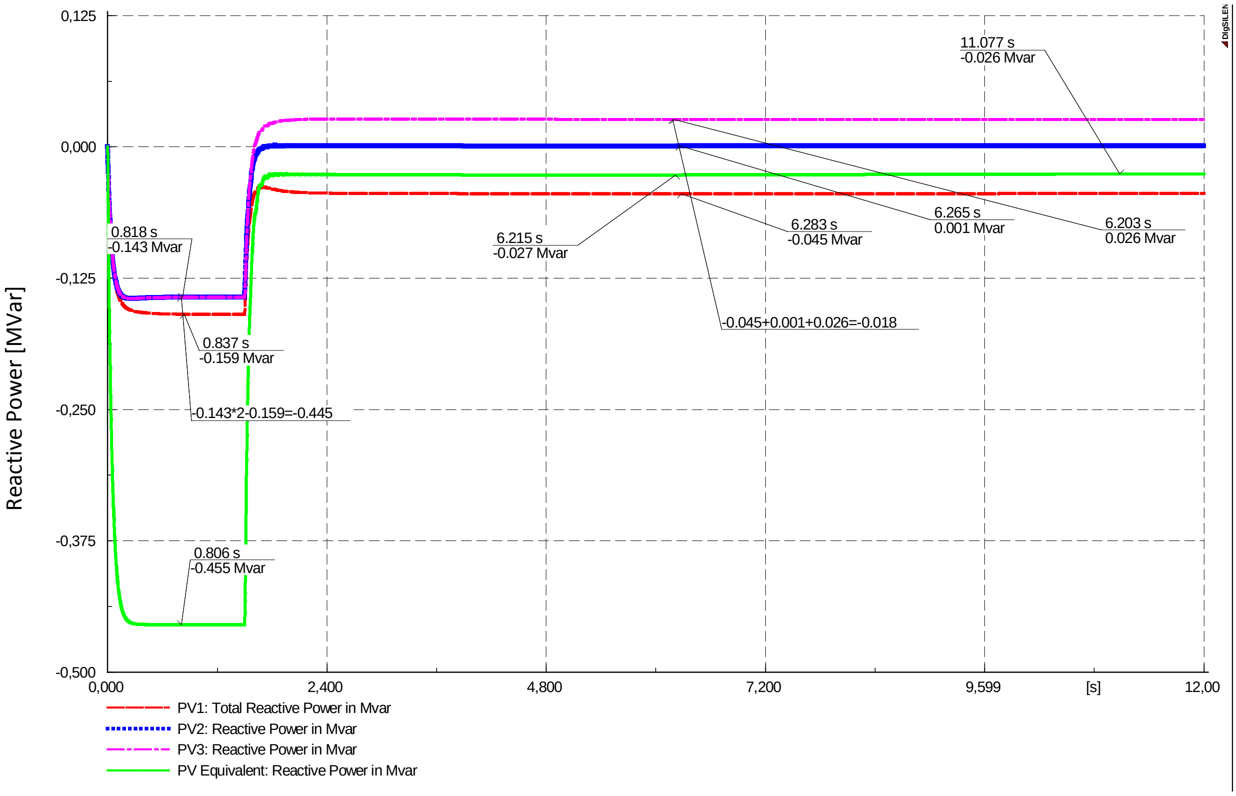
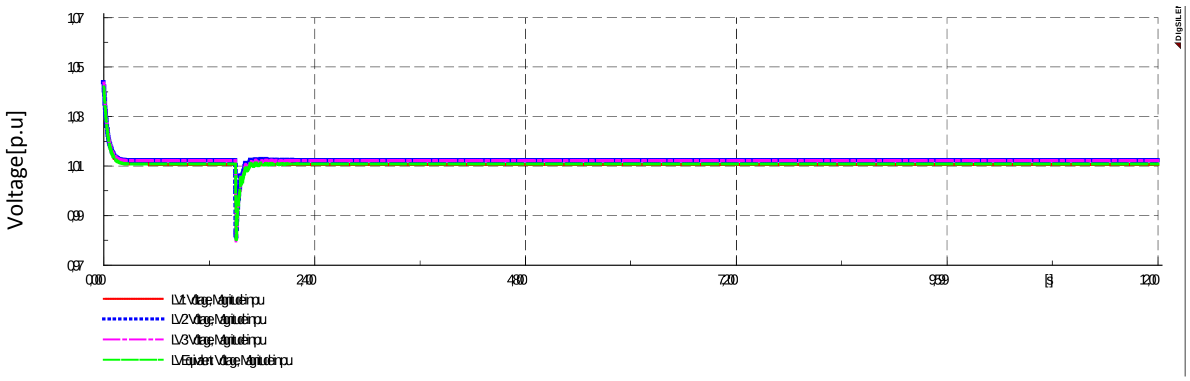
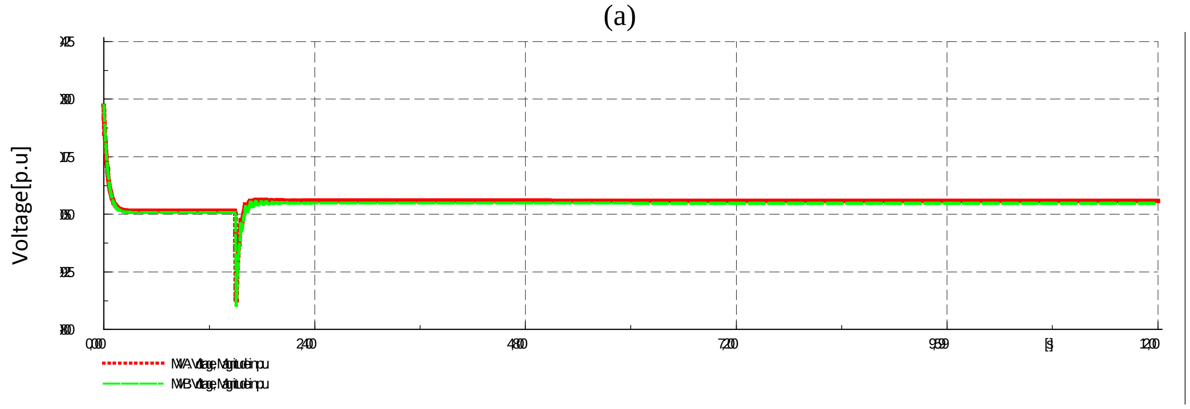


Fig. 18: Total reactive powers in scenario 4.



(a)



(b)

Fig. 19: AC voltages in scenario 4. (a) LV buses. (b) MV buses.

E. Scenario 5

In this scenario following assumptions are considered:

- Irradiance level is varied differently for PV systems in the non-aggregated model.
- In the non-aggregated model, individual transformers are not identical.
- Voltage controller parameters are different.
- PV systems are supposed to regulate the voltage at the LV bus.
- The voltage set-point is adjusted to 1.01 p.u.

In contrast to scenario 4, in this scenario voltage controller parameters of PV systems in non-aggregated model are also varied to make voltage controllers dissimilar. As mentioned earlier, the voltage controller is a pure integrator (I). In this scenario the integral gain of PV1 and PV2 voltage controllers are varied from -0.005 to -0.002 and -0.009, respectively, and the integral gain of PV1 voltage controller is kept as previous (-0.005). The results show that there is no difference in steady-state values compared to scenario 4. However, as can be seen in Fig. 20, the dynamic behavior of reactive powers is slightly different in scenario 5 compared to scenario 4.

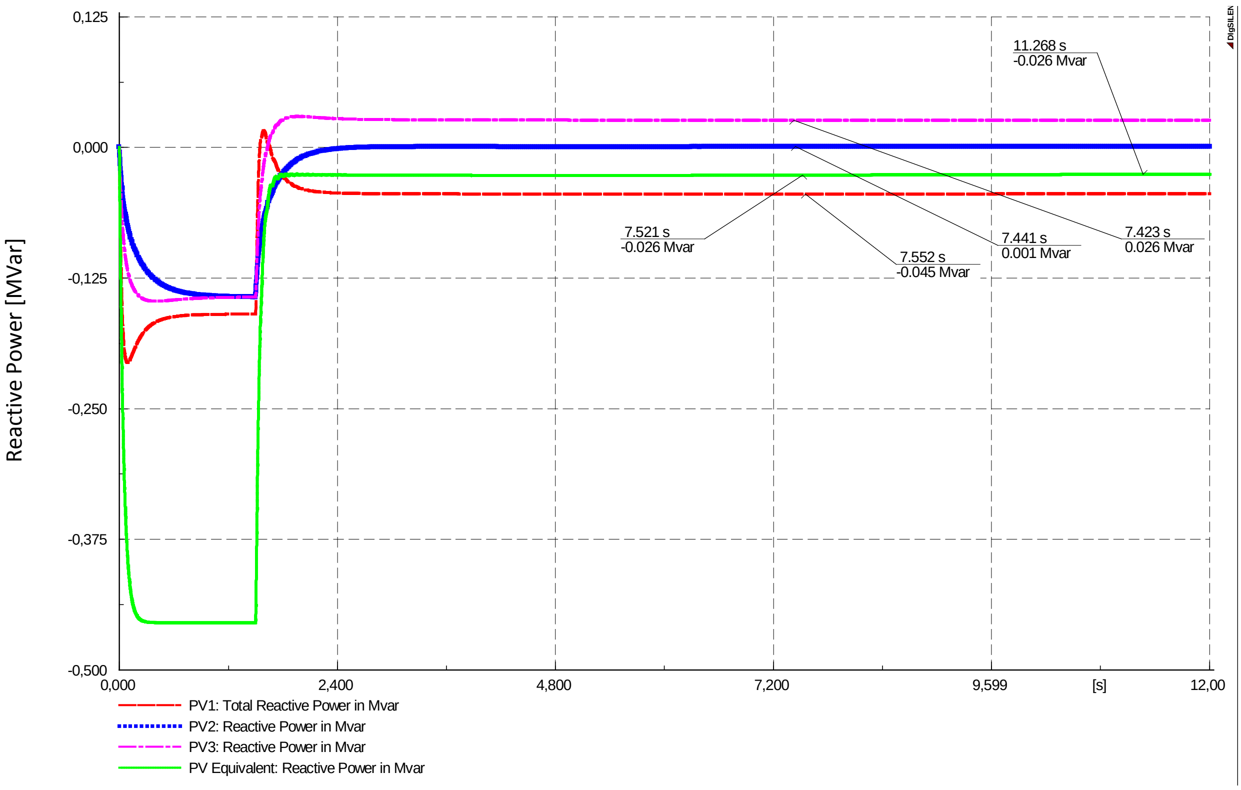


Fig. 20: Total reactive powers in scenario 5

F. Scenario 6

In this scenario following assumptions are considered:

- Irradiance level is varied differently for PV systems in the non-aggregated model.
- In the non-aggregated model, individual transformers are different.
- Voltage controller parameters are considered both identical and different.
- PV systems are supposed to regulate the voltage at the MV bus.

- The voltage set-point is adjusted to 1 p.u.

In contrast to scenario 4, in this simulation assumed that PV systems are supposed to regulate the voltage at the MV-bus. Moreover, the voltage controller is firstly assumed to be identical and then it will be changed.

In the case of similar voltage controllers, the results demonstrate that there is no difference in the total injected active power and dc-link voltage. However, there is significant change in the reactive power behavior. As shown in Fig. 21, reactive powers of individual PV systems in non-aggregated model are equally participating in the voltage regulation. In other words there is no reactive power circulation among individual PV systems. However, there is small deviation between total reactive power of aggregated and non-aggregated model that might be due to dissimilar individual transformers. Fig. 22 (b) shows that MV-bus voltages have been identically regulated.

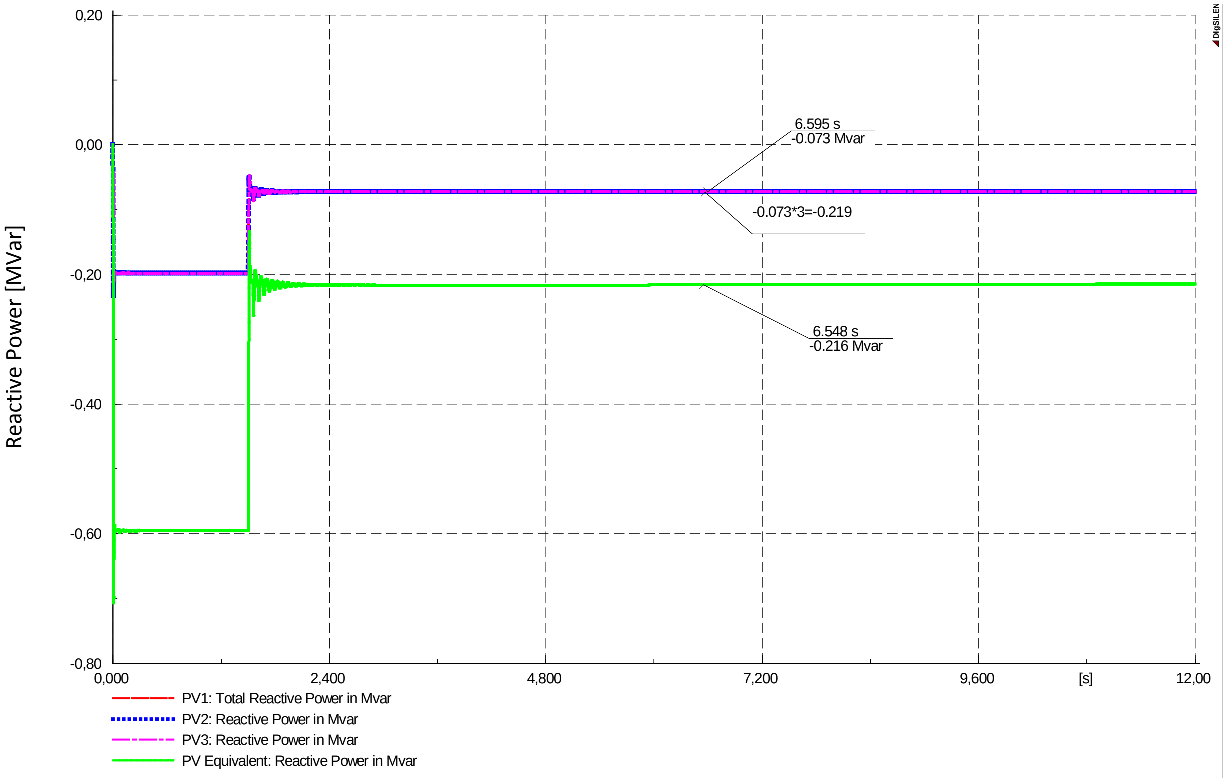
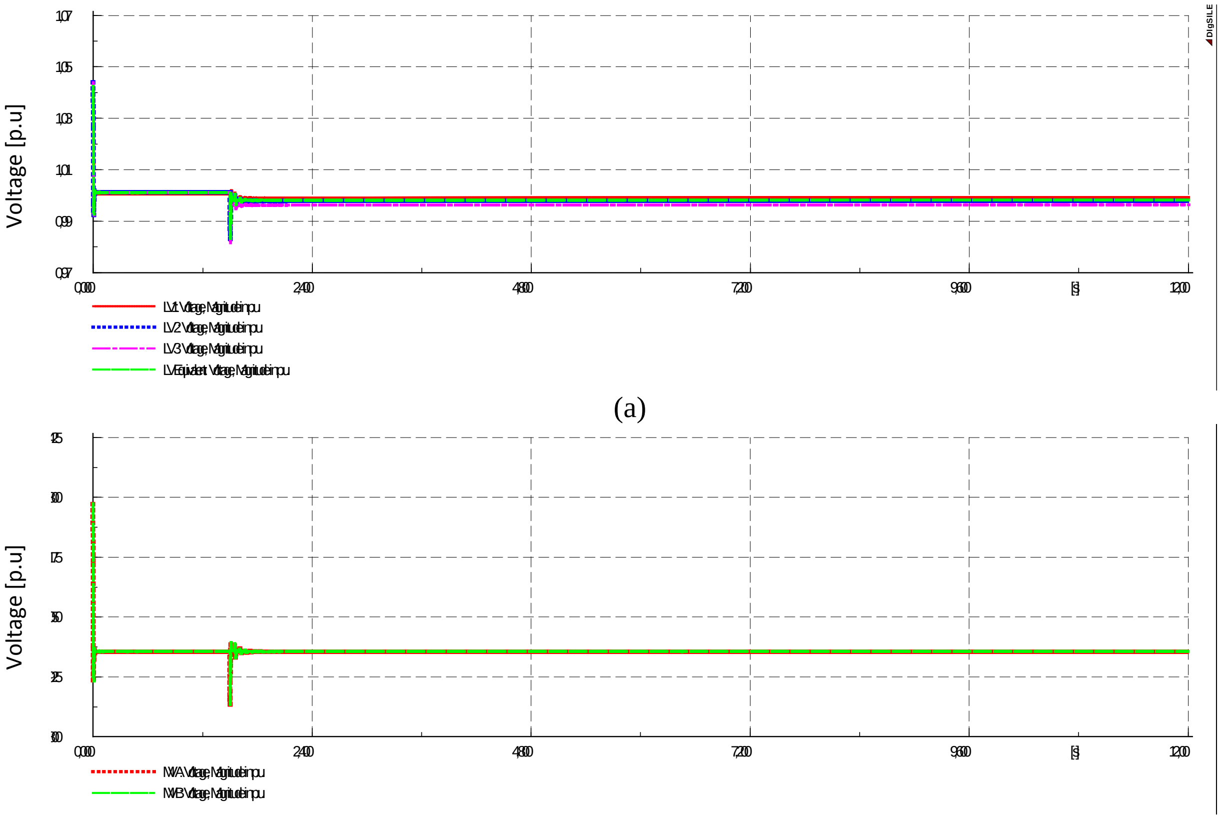


Fig. 21: Total reactive powers in scenario 6, similar regulators



(a)

(b)

Fig. 22: AC voltages in scenario 6 with similar regulators: (a) LV buses. (b) MV buses.

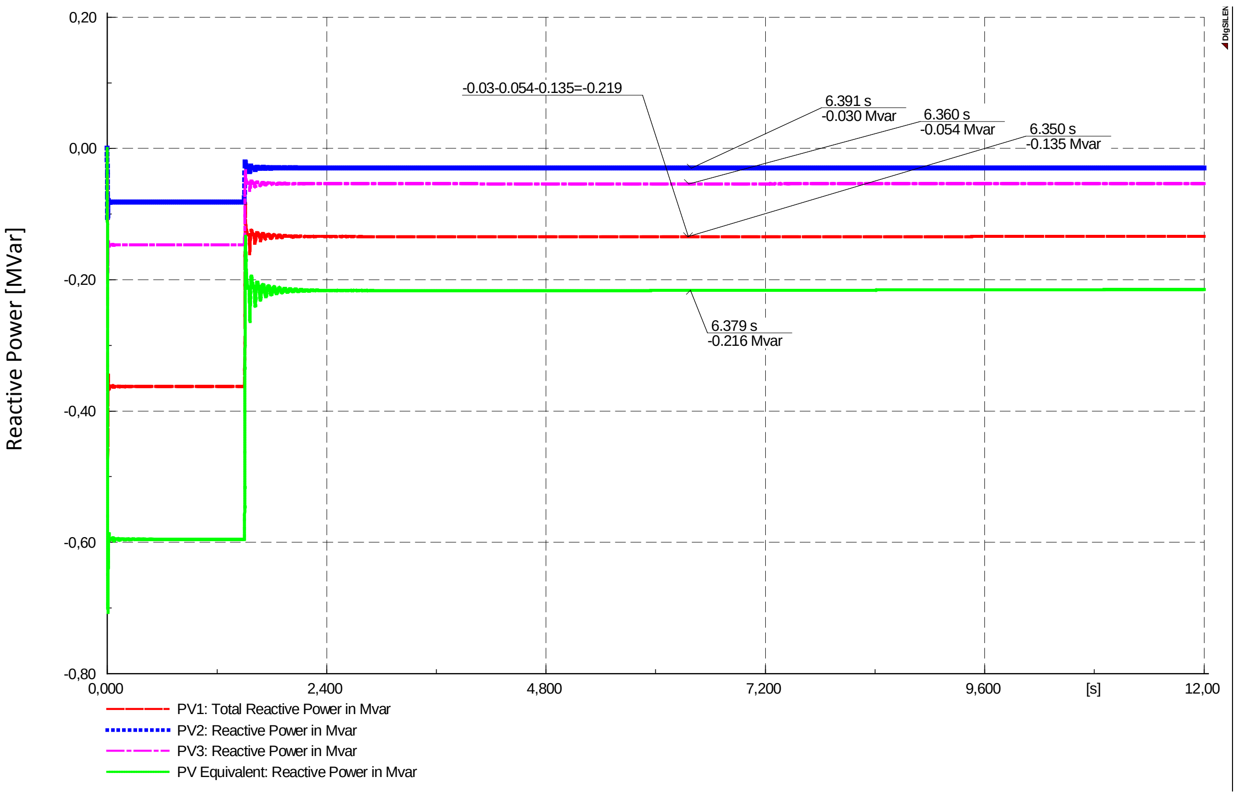


Fig. 23: Total reactive powers in scenario 6, dissimilar regulators

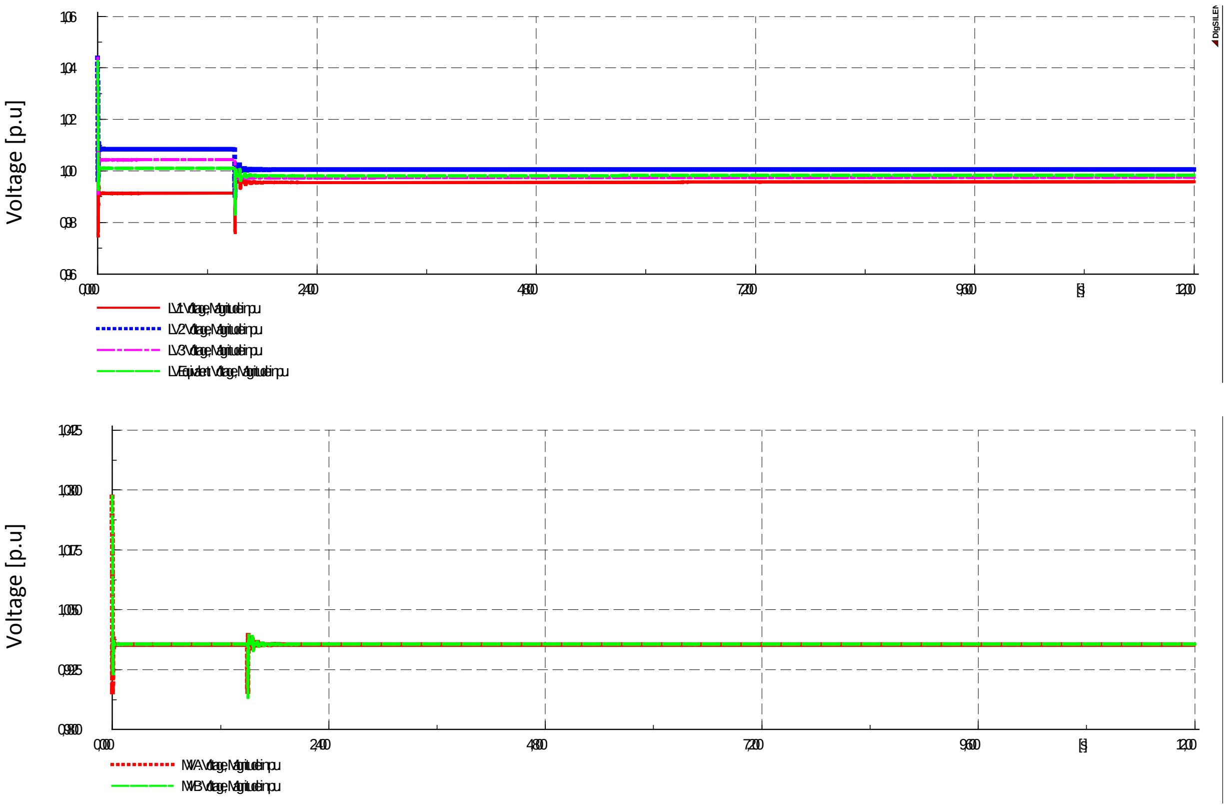


Fig. 24: AC voltages in scenario 6 with dissimilar regulators: (a) LV buses. (b) MV buses.

In order to consider the effect of different voltage regulator parameters, voltage regulator parameters are changed similar to the scenario 5. Fig. 23 depicts that reactive power contribution are not anymore equally distributed between individual PV systems in non-aggregated model. Nevertheless, the total reactive power of non-aggregated model (-*0.219 Mvar*) remains as previous. Fig. 24 (b) shows MV-bus voltages have been identically regulated.

VI. Conclusion

The bottom line of this study is that, although, reactive power operation mode of individual PV systems in non-aggregated model might be different (capacitive or inductive), the performance of the voltage regulator in both aggregated and non-aggregated model would be similar.

VII. References

[1] Mahmood F. Improving the Photovoltaic Modelin PowerFactory. 2012. EES Examensarbete / Master Thesis, XR-EE-ES 2012:017 http://www.diva-portal.org/smash/record.jsf?searchId=2&pid=diva2:571921