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Open Source Unified Power Flow Controller Model for Quasi-Static Time Series Simulation

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SUMMARY

New devices and controls are being developed and connected with the distribution system at historically unprecedented levels – this is especially true for devices that are connected at the "edge" of low voltage portions of the electric power system. Modeling and simulation is a crucial component to understanding the potential applications of these emerging technologies and ensuring the integration with distribution system planning and operations. However, due to the variety of products and vendors, the challenge when proposing a model is to make it flexible enough to cover different configurations, technical features and performance. By using the Open Source Distribution System Simulator (OpenDSS), EPRI proposes a flexible model for simulating Unified Power Flow Controller devices (UPFC) in Distribution Systems. This model can be customized by the user using a set of properties that describe the features of the device, its performance, operation bands and losses, among others characteristics. This paper presents the physical background for this model, the configuration modes and an example of utilization using sequential-time simulation in OpenDSS.

KEYWORDS

Digital simulation, distribution models, open-source software, planning, power electronic devices, UPFC.

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MODELING AND SIMULATING EMERGING TECHNOLOGIES

Advances in communications, power electronics, and advanced controls has resulted in a surge of new technologies, devices and sources that are connected beyond or near the customer meter. These technologies can dramatically alter distribution system operations and design by changing demand patterns, providing voltage support, and other operations.

Modeling and simulation are especially important for understanding the operation of these new technologies as well as ensuring their effective integration as part of the overall electric power system. Furthermore, the ability to accurately capture new technologies within distribution planning and operational tools will act to accelerate emerging technologies from small demonstration type stages to more widespread adoption across the system.

THE UPFC MODEL IN OPENDSS

Many of the devices being connected at the edge of the system are power electronic based – such as inverters or FACTS devices that have typically been deployed at the transmission system level. The universal power flow controller, or UPFC, is one such device. The UPFC model developed for EPRI's OpenDSS [1] is a generic device model for distribution level applications, where the aim is to regulate voltage for a part of the system and to compensate reactive power to fix a desired power factor (PF). The general architecture of the device model is shown in Figure 1.

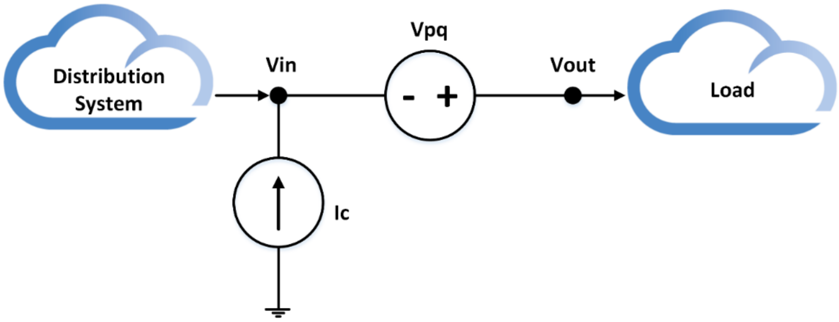

Figure 1.General architecture for the UPFC device.

This model is a steady state model and can be used for simulations in sequential-time mode. The variables defined to configure this device define its operational set point in terms of the output voltage and PF. Additionally, this generalized model allows the specification of the maximum rating for the compensating voltage source (Vpq) and the loss behavior as a function of the input voltage by using X-Y curves.

The UPFC model is consistent with the formulation of the power flow problem in OpenDSS, where the input variable are currents and the output variable are voltages as follows:

$$V = [Y_{BUS}]^{-1} I \tag{1}$$

Where Y_{BUS} is the nodal admittance matrix describing the interconnected power system network, I is the vector of injected currents and V represents the vector containing the voltages at the nodes of the system. Considering this approach the UPFC model is reformulated as shown in Figure 2.

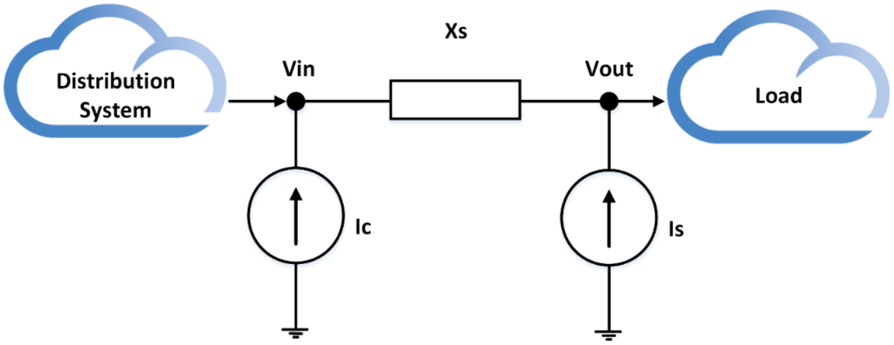

Figure 2. Current source approach for the UPFC device.

As can be seen in Figure 2, the proposed approach is based on injected currents on both sides of a reactor to simulate the effect of the coupling transformers and the inverters of the real model. The current source *Ic* emulates the effects of the current source for reactive power compensation at the input of the device in the real model, at the same time, by working together the current sources *Ic* and *Is* emulate the operation of the series voltage source for voltage regulation. Similar representations have been used in [2-4] and the details of the current injection approach can be found in these references.

The current source *Ic* is also used to adjust the losses to match model information provided by the user. The properties to define the features and operation of the UPFC device in OpenDSS are described in Table I.

TABLE I
UPFC Properties in OpenDSS

Property/Description	Property/Description	Property/Description
Bus1/ Is the name of the bus for the input (network side)	Phases/ The number of phases of the device	kvarLimit/ This value is the maximum amount of reactive power that the UPFC can compensate
Bus2/ Is the name of the bus for the output (load side)	Xs/ Is the impedance in ohms of the series transformer of the UPFC	LossCurve/ Is the name of the curve for modelling the losses of the device
RefkV/ Is the set point in kV for voltage regulation at the output	Tol1/ Is the desired tolerance for the control algorithm when regulating voltage	VHLimit/ This higher voltage limit. If the input voltage is higher than this limit the device will turn off
PF/ Is the desired power factor to be compensated at the input of the device	Mode/ A number that defines the operational mode of the UPFC (1 to 5)	VLLimit/ Is the lower voltage limit. If the input voltage is lower than this limit the device will turn off
Frequency/ the operation frequency of the device	VpqMax/ Is the Maximum voltage at the terminals of the impedance Xs	CLimit/ Is the current limit for the UPFC, if the current flowing through Xs is higher than this limit the device will turn off.
BaseFreq/ Is the Base frequency for impedance specifications	Enabled/ The device is enabled	RefkV2/ Second set point used for the operation modes that works with 2 reference bands

As can be seen in Table I, the device can be defined using a general description that includes its operational features, the physical construction and the losses generated by the device at different operation points.

The device losses

The losses for the UPFC device are defined as an X-Y curve that describes the behavior of the losses as a function of the input voltage. An example of a low-voltage UPFC loss curve is shown in Figure 3.

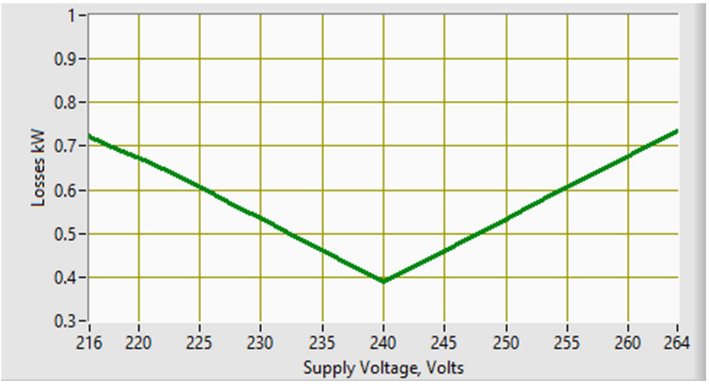

Figure3. Losses curve example

As can be seen in Figure 3, the losses are higher at the edges of the operational range of the UPFC while in the middle of the graph the losses are minimum. This point normally corresponds to the reference voltage *RefkV*. This curve can be interpreted as being related to the device required effort to reach the voltage set point at the output using series voltage compensation. It converts active power into reactive power for this purpose.

The UPFC device has 6 modes of operation: (0) *Controller in bypass mode*, (1) *voltage regulation only*, (2) *reactive power compensation only*, (3) *voltage regulation and reactive power compensation*, (4) *voltage regulation only using a secure band* and (5) *voltage regulation within a secure band plus reactive power compensation*. The mathematical theory for developing these control modes is described in [5].

Operation modes 1, 2 and 3

The operation modes 1, 2, and 3 are complementary. As mentioned above, the operation mode 1 will enable the device for voltage regulation only, operation mode 2 will perform reactive power compensation only and finally, operation mode 3 will combine modes 1 and 2 to offer both functionalities simultaneously. An example of the outputs when using the operation mode 3 is shown in Figure 4. As shown, the UPFC device is regulating the voltage at the load side (set point fixed = 244 VAC) and at the same time is compensating the PF at the grid side (PF = 1). Additionally, it can be seen how the PF regulation sometimes has some spikes These are present when the reactive power limit is reached (*kvarLimit*) and the UPFC device limits the reactive power compensation to its maximum capacity (5 kvar default). The voltage at the input of the device corresponds to a daily profile.

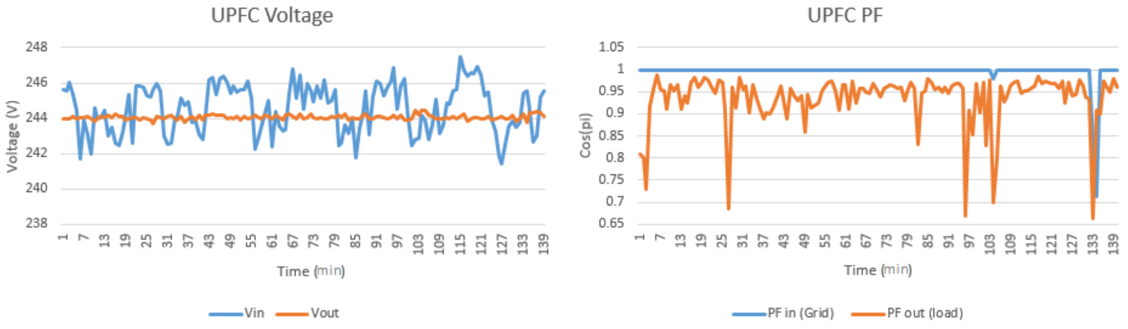

Figure 4. Voltage and PF when working with operation mode 3

Operation modes 4 and 5

In operation modes 4 and 5, the UPFC device works with 2 reference bands to create a zone where the UPFC performs no-control action. Similar to the relationship between operation modes 1, 2, and 3; the operation modes 4 and 5 differ in their control action by including the reactive power compensation functionality at the grid side. An example of the voltages obtained when working with mode 5 is shown in Figure 5. In this Figure the no-action band is between 244 and 240 VAC and the error tolerance is fixed to the 0.5%.

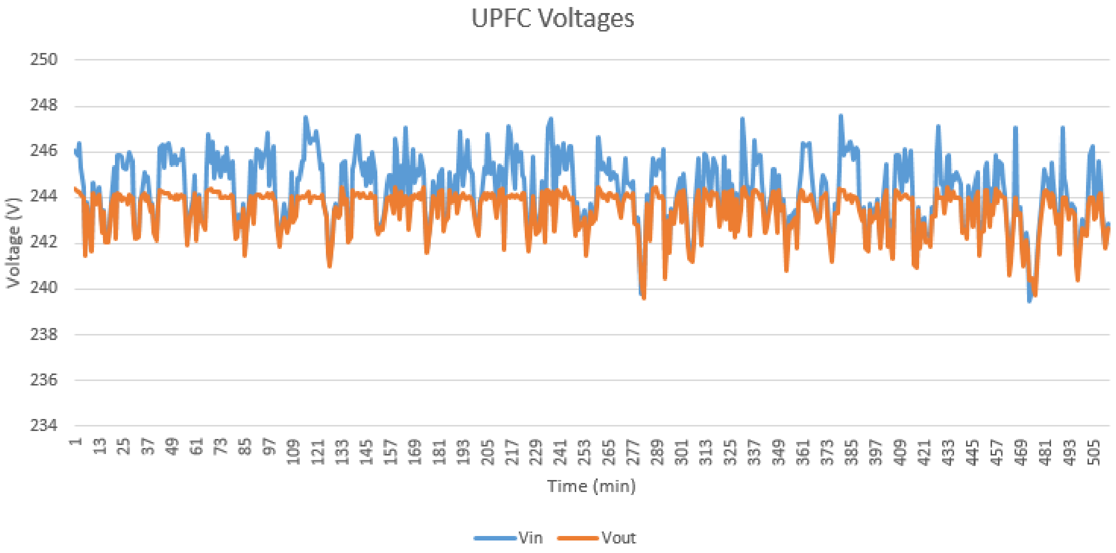

Figure 5. Voltages at the input and output of the UPFC model when working in mode 5

As can be seen in Figure 5, for the voltage at the input between 244 and 240 VAC there is no regulation performed. Basically, the voltage passes through the device. On the other hand, if the input voltage is higher than upper limit or lower than the bottom limit, the UPFC will regulate the output voltage to make it as close as possible to the closest reference. That is, if the input voltage is lower than the bottom reference the voltage will be regulated to this voltage. If the input voltage is higher than the upper reference, the voltage will be regulated to the upper reference.

The operation of the reactive power compensation is the same as in modes 2 and 3 and the same restrictions also apply.

APPLICATIONS

To show the performance of the proposed model in this section it is used to model a real device. The selected device is the Gridco LV-IPR50 [6], this device has a power rating of 50 kVA, compensates reactive power up to the 10% of rating leading or lagging, and works at 240VAC nominal single phase. The definition of this device for the OpenDSS UPFC model is as follows:

```
New upfc.TEST phases=1 bus1=UPFC_Input.1 bus2=UPFC_Output.1 refkV=0.24
mode=3 losscurve=Losses TOL1=0.005 Xs=0.02 kvarLimit=5
```

The loss curve is generated using representative example information delivered by the manufacturer (Figure 6). These curves are specified for each loading level and can be modelled in OpenDSS using a "XYCurve" object as follows:

New XYCurve.Losses npts=3 xarray=[0.9 1 1.1] yarray=[1.0143 1.008 1.0143]

As can be seen in the loss definition, the X -axis values are defined in terms of the reference voltage (240 VAC) and the Y-axis values will follow the demand. This is how the values for this axis are normalized. Therefore, the losses will be adjusted automatically when the load changes.

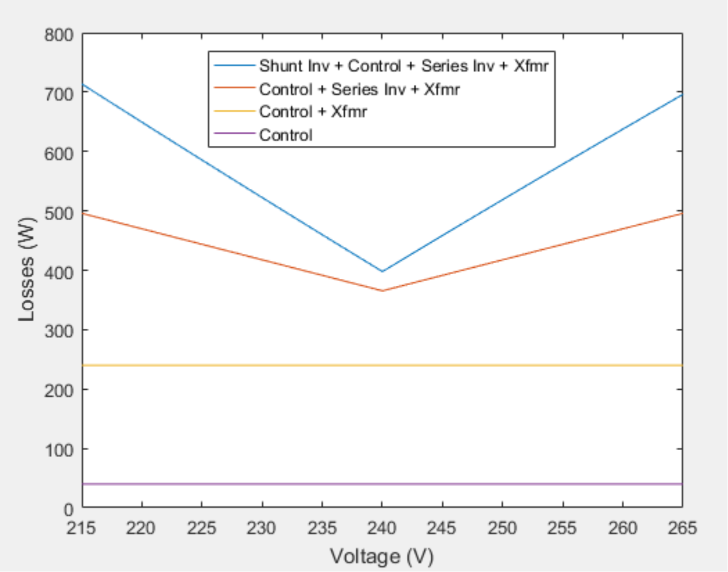

Figure 6. Losses proposed for the LV-IPR50 at nominal load (50kW)

The results when simulating the device working in mode 3 are shown in Figure 7. Additionally, the model has been used to validate data provided by real applications as shown in Figure 8. In this figure the simulation performed in OpenDSS is fed by using real data measured to validate the operation of the device and for planning purposes.

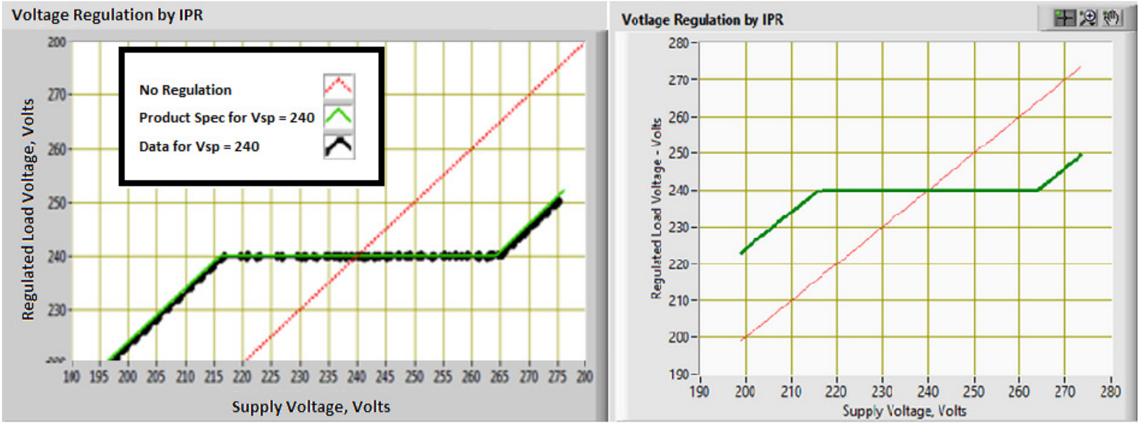

Figure 7. Input voltage vs output voltage: at the left the input/output for the LV-IPT50 provided by the manufacturer, at the right the input/output obtained from the simulated model.

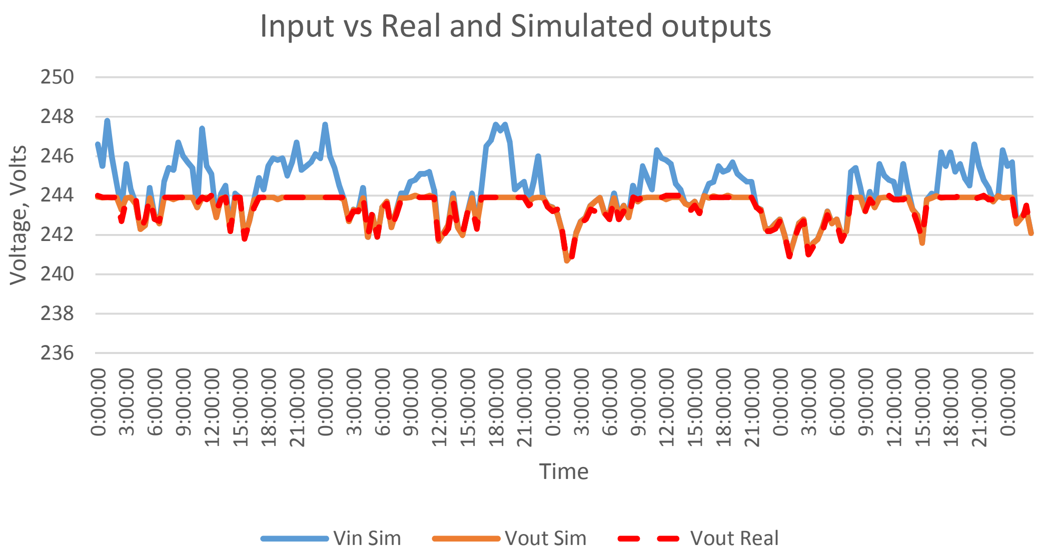

Figure 8. Real case Vs simulated case when simulating a customized UPFC device, Set point 244 VAC, lower limit 240 VAC.

CONCLUSIONS

We have presented an Open Source Unified Power Flow Controller for simulating Smart grid applications in Distribution Systems. This model is a comprehensive model that will allow to model a wide number of UPFC devices for research and developing using OpenDSS.

This paper has presented a general approach that can be used to perform sequential-time simulations, while giving OpenDSS users the opportunity to model their devices using a generalized framework, and for advanced users, the opportunity of improving its functionalities for custom applications.

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