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Use of Generic Dynamic Models for Photovoltaic Plants

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Abstract. Electricity production using photovoltaic systems is reaching such a high level in many countries that the system operators are introducing new connection requirements. To evaluate the fulfillment of these requirements, validated simulation models are needed. These models are evolving from manufacturer's user models to generic models as the ones proposed by the Western Electricity Coordinating Council (WECC). This paper discusses the need for generic models, introduces the photovoltaic plant model developed by WECC and presents a case of generic model parameterization, based on data from a commercial three-phase inverter, and model validation, by comparing simulation results with factory test data.

Key words

Modeling, Generic Model, Photovoltaic Plant, Model Validation.

1. Introduction

The contribution of solar photovoltaic generation to the electricity supply has grown exponentially in the last decade in many countries. In the beginning, most of the grid-connected photovoltaic installations were small commercial or residential plants with connection to the distribution network. As its impact on the network was small-scale, rarely a formal connection assessment based on technical studies and simulations were required. Today, however, the size and impact of PV systems is increasing and there are procedures and rules governing their connection to the grid [1]-[2]. To this end, it is necessary to have validated simulation models capable of representing the photovoltaic systems for the study of their behavior under steady and transient conditions.

In the literature different models are presented which vary according to their application and detail of modeling [3], although the current trend is to develop models for dynamic simulation adapted to different network codes [4]. This is the choice made by the manufacturers of inverters who are in need of developing user models to validate their plants against different grid codes. However, this approach poses some drawbacks such as the difficulty of participation in the design and commissioning processes of the plant by the various stakeholders involved and the difficulty of managing many different models by system operators.

Therefore, there is a need for open standard models of photovoltaic plants, both for individual components and for their central control systems [5]. The standardization work carried out by the Western Electricity Coordinating Council (WECC), through its working group on modeling and validation, as well as the work done within the working group 27 of the Technical Committee 88 of the IEC, can be highlighted as good steps in this direction.

This paper introduces the needs, requirements and development of generic dynamic models of photovoltaic systems for network studies, along with their use and validation. An example is presented of the configuration of the generic model for a commercial inverter and its validation against factory tests.

2. Evolution of Generic PV Dynamic Models

The first generic model for photovoltaic plants was based on a generic model already developed for wind generation. Specifically, the initial model proposed by WECCs is based on the full converter wind model "Type 4" or WT4, shown in Figure 1 [6]. It is composed of two models. The converter model injects active and reactive power components into the network from its terminal voltage and the current references calculated by the control model. The control model is basically a reactive power-voltage controller that, in addition to the original Type 4 model, allows changing the active power setpoint externally to simulate irradiance variations.

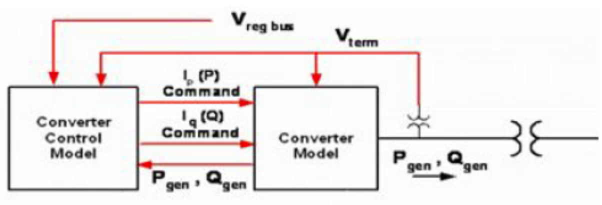

Fig. 1 WT4 model structure

This model has evolved into a generic positive sequence renewable plant model with central control [7], in which the dynamics of the DC side are not modeled. Thus, the model can be applied to any type of renewable generation plant connected through inverters to the grid, as in the case of PV plants. This new model has already been implemented in some simulation software tools, such as PSLF, PowerWorld or PSS/E, in which this paper is based.

3. WECC Generic Renewable Generator Model

A. Model structure

Generic Renewable Generator Model developed by WECC seeks to capture the main dynamics of photovoltaic plants with central control at the point of connection (PCC) to a transmission grid. By selecting appropriate values of the model parameters, inverter manufacturers may represent the specific operation of their equipment.

It is a positive sequence model used for analyzing balanced power system phenomena in a frequency range from 0 to 10 Hz. The model is divided into three blocks; each one models a part of the plant, as shown in Figure 2.

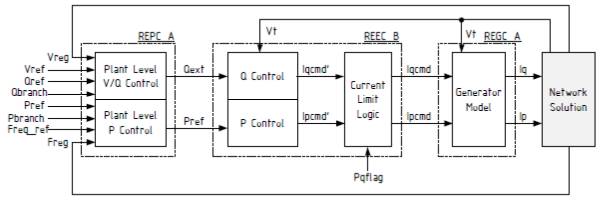

Fig. 2 Generic Renewable Generator Model structure

The generator model (REGC_A) represents the current injection to the network by the converter and it is similar to the model used in the WT4 model. The electrical control model (REEC_B) is an evolution of the model used in WT4 model, and it includes an improved model of the inverter performance during voltage sags, based on a table of current injection. Finally, the central control model (REPC_A) allows representing the P-f and Q-V control performed by the central controller of the PV plant.

B. Generator model

The generator model, shown in Fig. 3, calculates the current injected into the network by the inverter in normal and in perturbed operating conditions, when the voltage in the PCC is outside steady state limits.

In case of high voltage transient operation, the current injection logic limits the reactive current injection to avoid contributing to the voltage rise. Besides, in case of low voltage transient operation, as voltage sags created by faults, the active current injection logic mimics the response of the inverter PLL control, as well as the active current injection after the voltage returns to normal level (activated by Lvplsw signal).

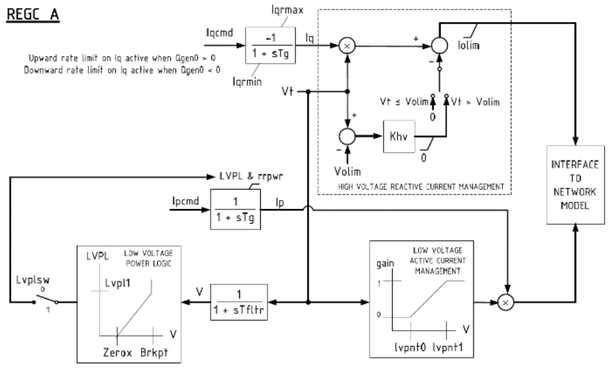

Fig. 3 Generator model (REGC_A)

The generator model can include max/min voltage and frequency protection functions but, in the WECC specification, this functions can be done using external models with similar functionality. This is the approach followed by the software vendors that have included the WECC models into their simulation packages.

C. Local control model

REEC_B local control model, shown in Fig. 4, improves the performance of the electrical control model used in WT4 model with a supplementary reactive current injection signal (iqinj). Additionally, in the implementation done in PSS/E software, the model includes a state machine to represent the performance of the inverter under various grid codes that require temporary supplementary reactive current injection after a low or high voltage disturbance.

The model includes the active and reactive power controls at the inverter terminals. The controls determine the active and reactive current setpoints for the generator model in normal operating conditions, including a current limiting function with configurable active or reactive power priority.

Active power control keeps a reference value between the maximum and minimum inverter limits and it can include ramp up and ramp down limits. The active power reference is determined from the initial power flow solution or from the plant control.

Reactive power control can be configured in power factor or reactive control mode and it is based on cascaded PI regulators that determine the voltage setpoint for the inverter terminal. In addition, it is possible to derive the reactive power reference from the inverter terminal voltage.

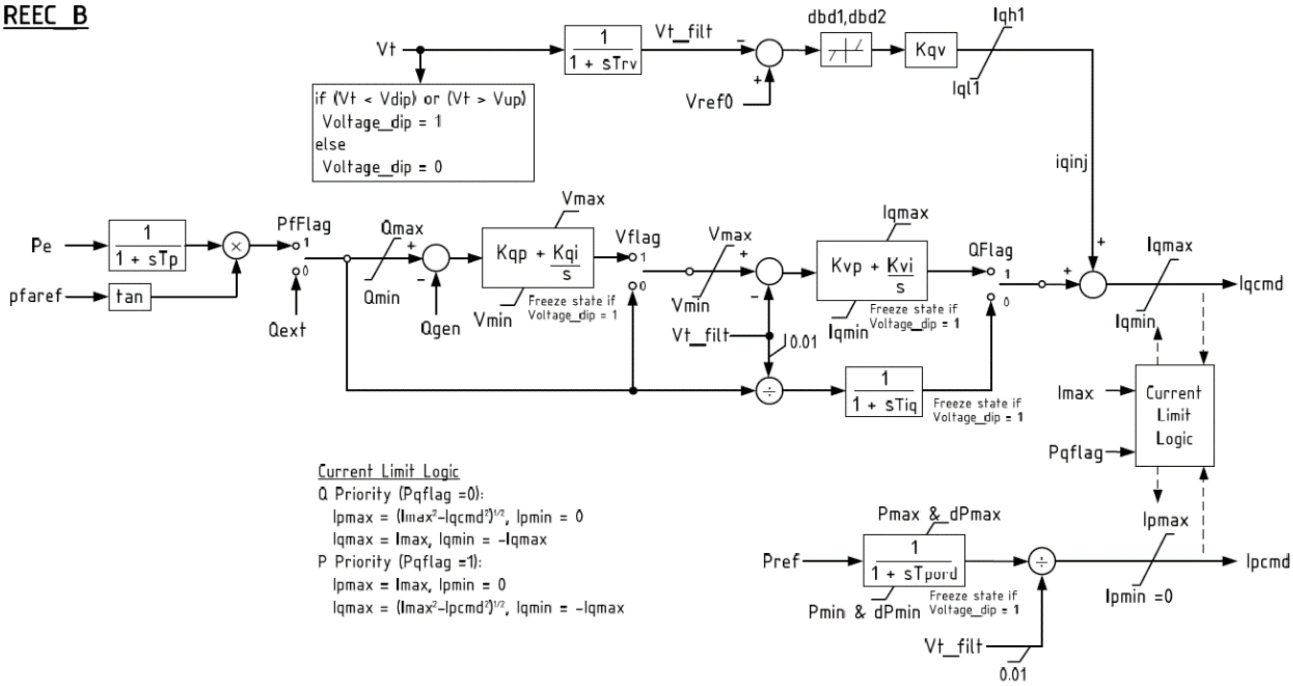

Fig. 4 Local control model (REEC_B)

D. Central control model

Finally, the central control model (REPC_A), shown in Fig. 5, allows to reproduce the P-f and Q-V controls done by a central PV plant controller. This model is only for those grid codes that allow representing the PV plant using an aggregated inverter model.

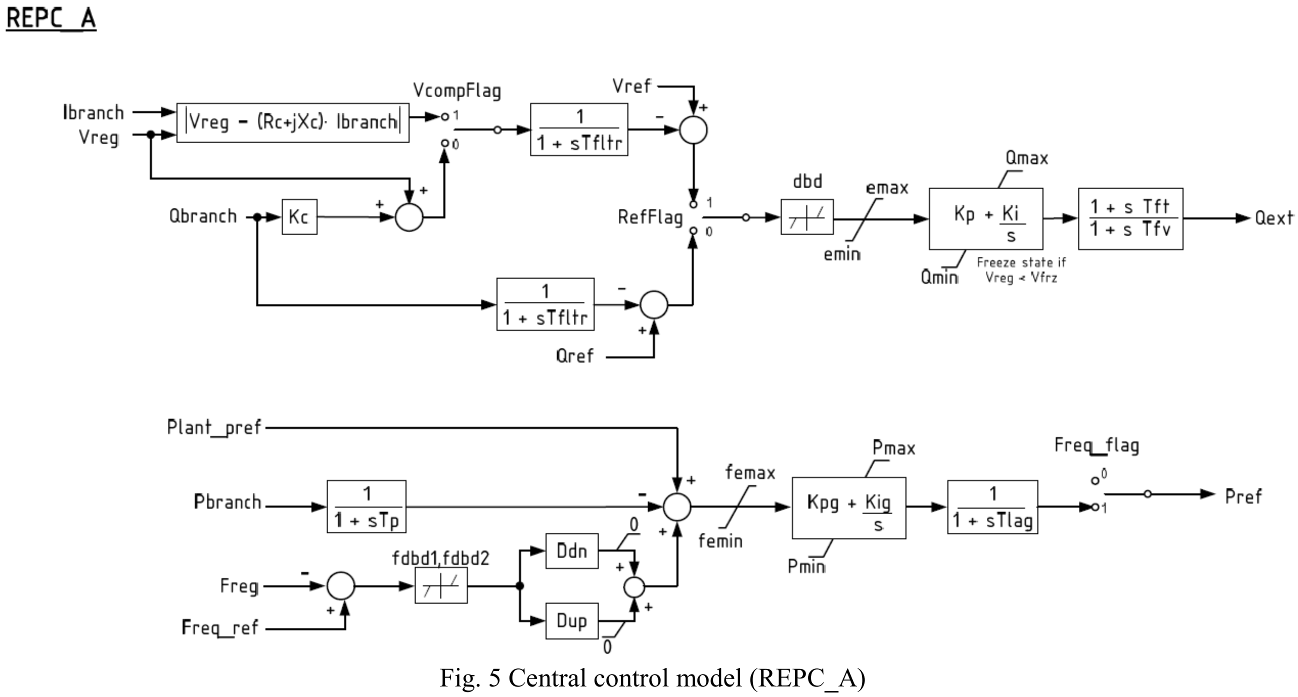

Fig. 5 Central control model (REPC_A)

Reactive power control controls the voltage at the connection point, or at another point in the grid compensated by current. It can also operate controlling the reactive power flow in a branch, usually the interconnection line.

Active power control controls the active power produced by the plant in a branch including primary frequency response based on a proportional regulator with deadband and ramp up and down limits.

Configuring the different flags of the central and local control models, it is possible to adapt the functionalities of the PV model to the requirements of different grid codes [7].

4. Commercial Inverter Model Validation

In this section the use of WECC Generic Renewable Generator Model is presented to model the behavior of a commercial three-phase inverter with the following ratings: 140 kVA, 220 V and 368 A maximum current.

The simulation has been done with the software PSS/E, which includes the WECC generic renewable generator model in their latest versions. The model has been parameterized according to the characteristics of the inverter and this parameterization has been validated by comparing the results of different simulations with those obtained by testing.

As an example, Figures 6 and 7 show the factory test results of a three phase sag test with 0% residual voltage. Fig. 6 shows the three phase voltages applied during the test and Fig. 7 the apparent, active and reactive power injected by the inverter. During the voltage sag, the active and reactive power falls to zero and, after the voltage recovers, the inverter returns to the prefault state following an active power ramp. During the recovery transient the inverter injects reactive power to support the voltage at the terminals, returning to the prefault value once the voltage recovers.

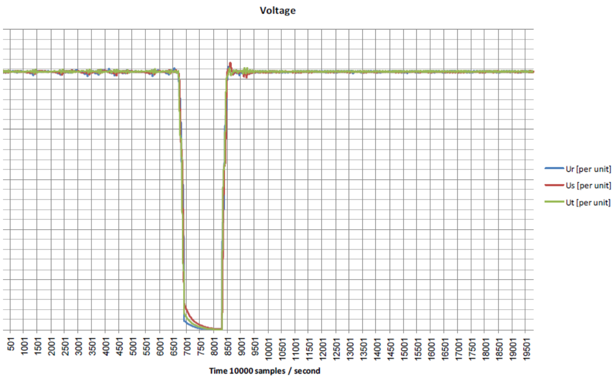

Fig. 6 Three phase 0% voltage sag test. Test Voltage

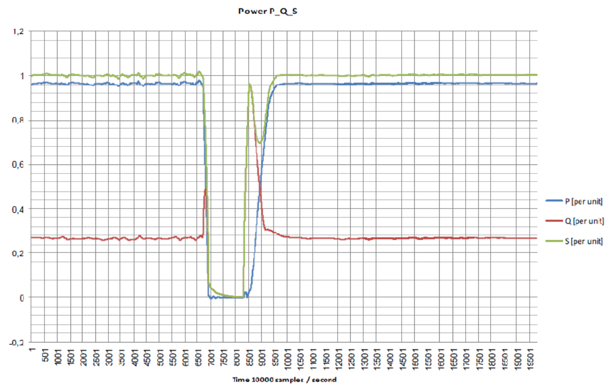

Fig. 7 Three phase 0% voltage sag test. Inverter response

In order to simulate the inverter response with the generic model, one of the practical problems is to reproduce the same voltage profile in the simulation software than the profile applied during the factory test. Regarding PSS/E software, it is not possible to assign the voltage test data to a generator. To solve this issue two solutions can be used: simulate a fault or use a test voltage user model.

The first solution consists on generating the sag simulating a three phase fault with the same duration and the right fault impedance to match the voltage fall. For the test case of Fig. 6, the solution is shown as the blue curve (V1(pu)-Zf=0) in Fig. 8. Comparing this solution with the test voltage (red curve in Fig. 8), a clear difference exists during the voltage fall and the voltage rise. These differences cause a different response of the simulated model, because the operation mode of the inverter changes with the terminal voltage. This way, it is not possible to validate the model against test measurements.

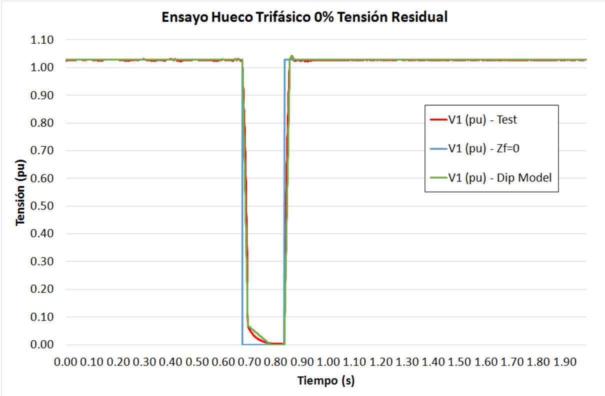

Fig. 8 Test voltage (red), three phase zero fault resistance voltage (blue), sag model voltage (green)

To solve this problem, the second solution has been followed in this paper, using the procedure proposed by Ledesma and Gallardo [8]. A new user model has been assigned to a generator in the PSS/E case. This model operates as a voltage source whose voltage profile can be parameterized using a table of 7 pairs of voltage-time points. The result of the adjustment process is shown as the green curve (V1(pu) – Dip Model) in Fig. 8. This curve clearly gives a better adjustment to the voltage profile applied in the factory tests.

For the validation tests, the test network shown in Fig.9 has been created, composed of two generators connected by a zero impedance line. The generator connected to TEST bus represents the test source and is modeled with the programmable voltage source user model. The generator connected to PV bus represents the inverter and is modeled with the WECC generic model, which is a current injection model. To avoid convergence errors in the network solution during the dynamic simulation, a resistive load has been added with a demand equal to the rated power of the test source. Appendix 1 contains the network RAW data.

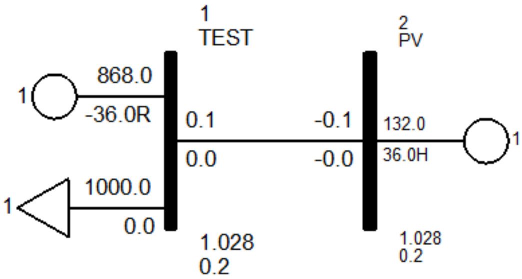

Fig. 9 Three phase 0% voltage sag test. PSS/E test setup

The results of the model validation for a three phase sag with 0% residual voltage are shown in Fig. 10 and 11. Comparing these figures with Fig. 6 and 7, it can be concluded that the generic model, with the parameterization shown in Appendix 2, has the same behavior as the commercial inverter tested except for the transient peak in the reactive power response at the beginning of the sag.

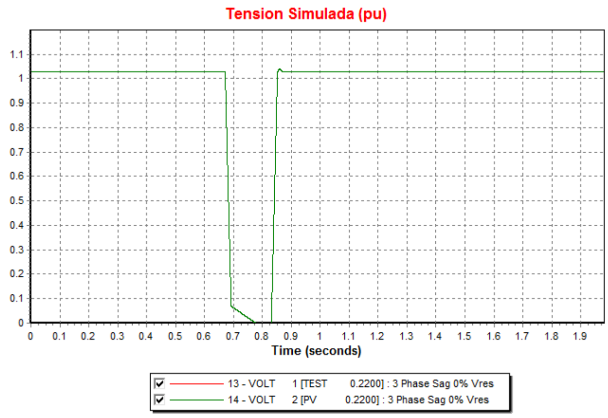

Fig. 10 Three phase 0% voltage sag test. Simulated Voltage

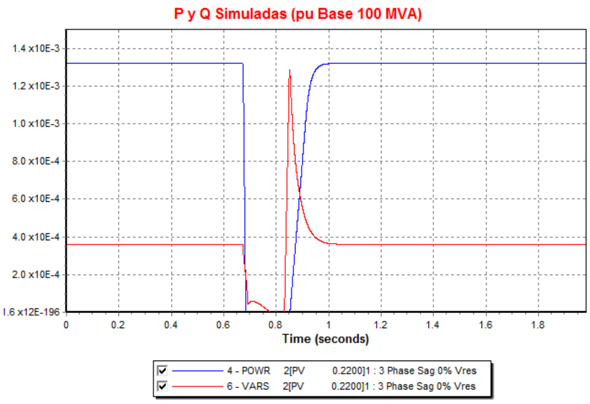

Fig. 11 Three phase 0% voltage sag test. Simulated inverter response

For an easy comparison of test and simulation results, Fig. 12 overlays the data for active and reactive power in the same graph.

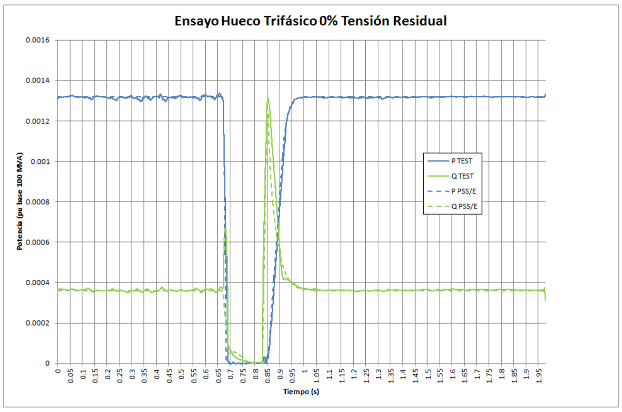

Fig. 12 Three phase 0% voltage sag test. Test data and PSS/E results

5. Conclusions

The development of generic models of photovoltaic plants is presented as a step in the right direction to increase the penetration of this type of generation in the power system. This article has justified the need for this type of models, it has shown its evolution and it has presented an example of application of modeling of a commercial inverter validated against factory test

The generic model allows representing the aggregate behavior of a photovoltaic plant with an inverter equivalent. However, in those connection regulations requiring a complete model of the plant, it is necessary to use a plant control model different from the generic one presented here. Nowadays, this model remains a user model provided by the manufacturer of the inverter or by the plant promoter.

Acknowledgement

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Appendix 1. Test Network RAW Data

```
0,   100.00, 33, 0, 1, 50.00     / PSS(R)E-33.4    FRI, NOV 7 2014  13:48
TEST NETWORK FOR MODEL VALIDATION

     1,'TEST        ',   0.2200,3,   1,   1,   1,1.02800,   0.0000,1.10000,0.90000,1.10000,0.90000
     2,'PV          ',   0.2200,2,   1,   1,   1,1.02800,   0.0000,1.10000,0.90000,1.10000,0.90000
0 / END OF BUS DATA, BEGIN LOAD DATA
     1,'1 ',1,   1,   1,     1.000,     0.000,     0.000,     0.000,     0.000,     0.000,   1,1,0
0 / END OF LOAD DATA, BEGIN FIXED SHUNT DATA
0 / END OF FIXED SHUNT DATA, BEGIN GENERATOR DATA
     1,'1 ',      0.868,     -0.038,      1.000,     -1.000,1.02800,      0,      1.000, 0.00000E+0, 1.00000E-5, 0.00000E+0,
0.00000E+0,1.00000,1,  100.0,     1.000,    -1.000,   1,1.0000
     2,'1 ',      0.132,      0.038,      0.038,      0.038,1.00000,      0,      0.137, 0.00000E+0, 9.99900E+3, 0.00000E+0,
0.00000E+0,1.00000,1,  100.0,     0.137,     0.000,   1,1.0000,   ,    ,   ,    ,   ,    ,1, 1.0000
0 / END OF GENERATOR DATA, BEGIN BRANCH DATA
     1,     2,'1 ', 0.00000E+0, 1.00000E-4,  0.00000,     0.00,     0.00,     0.00, 0.00000, 0.00000, 0.00000, 0.00000,1,1,   0.00,
1,1.0000
0 / END OF BRANCH DATA, BEGIN TRANSFORMER DATA
0 / END OF TRANSFORMER DATA, BEGIN AREA DATA
0 / END OF AREA DATA, BEGIN TWO-TERMINAL DC DATA
0 / END OF TWO-TERMINAL DC DATA, BEGIN VSC DC LINE DATA
0 / END OF VSC DC LINE DATA, BEGIN IMPEDANCE CORRECTION DATA
0 / END OF IMPEDANCE CORRECTION DATA, BEGIN MULTI-TERMINAL DC DATA
0 / END OF MULTI-TERMINAL DC DATA, BEGIN MULTI-SECTION LINE DATA
0 / END OF MULTI-SECTION LINE DATA, BEGIN ZONE DATA
0 / END OF ZONE DATA, BEGIN INTER-AREA TRANSFER DATA
0 / END OF INTER-AREA TRANSFER DATA, BEGIN OWNER DATA
0 / END OF OWNER DATA, BEGIN FACTS DEVICE DATA
0 / END OF FACTS DEVICE DATA, BEGIN SWITCHED SHUNT DATA
0 / END OF SWITCHED SHUNT DATA, BEGIN GNE DATA
0 / END OF GNE DATA, BEGIN INDUCTION MACHINE DATA
0 / END OF INDUCTION MACHINE DATA
Q
```

Appendix 2. Dynamic DYR Data

```
1 'USRMDL'  1 'VTEST'  1  0  0  14  0  2 1.0 0.6715 0.067 0.6920 0.0 0.7780 0.0 0.8310 1.0 0.852 1.014 0.86 1.0 0.87 /
2 'USRMDL' 1  'REGCAU1'  101   1   1   14   3   4   1      0.20000E-01   12.000   0.90000   0.40000   1.1000
1.2000   0.80000   0.40000   -1.0000   0.20000E-01   0.70000   9999.9   9999.9   1.0000   /
2 'USRMDL' 1  'REECAU1'  102   0   6   45   6  9  0   0   1   0   0   0
0.90000   1.1000   0.20000E-01   0.0000   0.0000   2.0000   1.0000   -1.0000   0.0000
0.0000  0.0000   0.0000   0.20000E-01   0.44000   -0.44000  1.1000   0.90000   0.50000   0.0000
25.000   0.0000   0.0000   0.20000E-01   2.0000   -2.0000   1.0000   0.0000   1.0000   0.10000E-01
0.10000   1.0000   0.40000   1.0000   0.60000   1.0000   1.0000   1.0000   0.10000   1.0000
0.40000   1.0000   0.60000   1.0000   1.0000   1.0000   /
```