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Voltage dip model in PSS/E

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Abstract

This paper shows in detail a model of a voltage dip in the power system dynamic simulation tool PSS/E. The modelled voltage dip corresponds to a specification published by the Spanish System Operator Red Eléctrica de España. Dynamic simulations involving this voltage dip are interesting for wind energy producers because any wind farm in Spain which is able to remain connected and stable after such a dip will receive an economic revenue. The source code of the model is shown and commented. Results of a simulation involving the voltage dip and a fixed-speed windmill are shown in order to illustrate the performance of the model.

Key-Words

Voltage dip, transient stability, power system dynamics, wind energy

I. INTRODUCTION

WIND power installed in the Spanish peninsula, which has been growing continuously over the last decade, reached 8.2 GW at the end of 2004 [1]. This is a significant amount of installed capacity, taking into account that the maximum demand at the same area and the same year was 37.7 GW. Thus, depending on the weather and the power demand, a large percentage of energy may be produced by wind farms. This situation is more likely to happen at windy nights, when the load is low and the wind power production is high.

As a result of the increase in wind power production, concern has arisen about the effect of voltage dips on the transmission grid. These voltage dips, which may be caused by short-circuits on the high-voltage network, propagate over a wide area and may cause the disconnection of a large number of wind farms, compromising seriously system stability. In order to avoid or minimise this risk, several system operators from areas with high wind power penetration have published technical specifications to allow the connection of wind farms to the grid [3], [4].

In the same direction, the Spanish System Operator Red Eléctrica de España, together with delegates from private companies from the wind energy sector, has developed technical specifications requiring from the wind farms to remain connected after a voltage dip [2]. This dip is defined as a voltage decay followed by a voltage recovery in two ramps with different slope. Wind installations which remain connected after such a dip will obtain an economic prime.

The publication of the voltage dip has prompted windmill manufactures to perform test and simulations on their machines, in order to know if their windmills will remain connected after such voltage dip, and to take the appropriate measures if this is not the case. In order to perform these simulations, it is necessary to model the voltage dip in software tools suitable for power system analysis. One of these tools is PSS/E from PTI, which is extensively used by a large number of electric utilities.

This paper proposes a model in PSS/E for the voltage dip described by the Spanish System Operator, and may be used as a guide to develop a model of any other voltage dip.

The paper is basically divided into three parts. The first one describes briefly the voltage dip as established by the Spanish System Operator specification. The second one describes in detail the implementation of the voltage dip model in PSS/E, including the source code. The third one shows an example of the application of the voltage dip model to the study of the performance of a fixed-speed windmill.

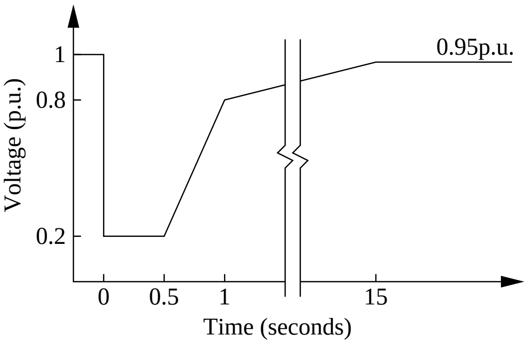

Fig. 1. Voltage dip as specified by the Spanish System Operator

II. VOLTAGE DIP SPECIFICATION

Fig. 1 show the voltage dip specified by the Spanish System Operator. It consists of a voltage decay to 20 % of the nominal value during 0.5 seconds, followed by a voltage recover in two ramps: one from 20 % to 80 % of the nominal value in 0.5 seconds and one from 80 % to 95 % of the nominal value in 14 seconds. The voltage dip is applied simultaneously to the three phases at he affected bus.

III. VOLTAGE DIP MODEL IN PSS/E

This section describes in detail the implementation of the voltage dip depicted in fig. 1 in PSS/E. The model is written in fortran, and it is implemented as a special case of a rotating machine model. Rotating machines are actually represented in PSS/E by Norton equivalents, but for the sake of clarity, we will refer to them in this paper as Thevenin equivalents, corresponding generally to a transient or subtransient voltage source behind a transient or subtransient impedance. In order to model the voltage dip, the impedance of the Thevenin equivalent, named ZSORCE in PSS/E, is set to a very small value (10^{-6} p.u. in the simulations), so that the internal voltage is imposed at the bus where the model is connected. This internal voltage is forced to be that of the voltage dip.

The model has no constants (named CONs in PSS/E), no integer constants (ICONs) and no state variables (STATEs) as it does not include any differential equation. It only uses two variables (VARs) which must be retained during the different call to the model. This variables account for the real and the imaginary part of the voltage at the initial moment, in order to begin the simulation with all the derivatives equal to zero.

As the model follows the conventions of the generator models, it must be refered at the dynamic data file as a generator model. The entry point for the voltage dip model at the dynamic data file (read by PSS/E through the activity DYRE) has the form

```
IBUS 'USRMDL' MAQID 'GENIND' 1 0 0 0 0 2
```

Where IBUS is the number of the bus where the voltage dip is imposed, and MAID is the number of the machine which stands for the voltage dip model. This machine should have a very small ZSORCE value, as discussed above. The number 1, according to the PSS/E specifications for model writing, means that it is a generator model. The first number zero means that it does not impose a current injection into the bus where it is connected (instead, it acts as a Thevenin equivalent). The third, forth and fifth zeros mean that there are not real constants, neither integer constants, neither state variables. The number 2 mean that the model keeps memory space for two global variables.

The structure of the voltage dip model, as any generator model in PSS/E, has three different entry points: one for the calculation of the initial conditions, one for the calculation of the rate of change of the state variables, and one for the calculation of other output variables.

The name of the subroutine that contains the model is REEDIP. The first lines are for variable declaration and general asignations:

```
      SUBROUTINE REEDIP(MC,ISLOT)
$INSERT COMON4
      integer MC,ISLOT,IB,IB0,IBUS,I
      complex jay,ibus,VDIP
C
      IB0 = NUMTRM(MC)
      IB = ABS(IB0)
      IBUS = NUMBUS(IB)
      MAQID = MACHID(MC)
      I = STRTIN(4,ISLOT)
      jay = (0.,1.)
      GOTO (100,200,300) MODE
```

The first entry point, which is called at the beginning of the simulation, is used to store the value of the voltage at the initial point. The variable VDIP will be used always to represent the value of the voltage during the voltage dip. Several operations must be performed because the relevant variable for the PSS/E is the current source ISORCE of the Norton equivalent, instead of the VDIP voltage value of the Thevenin equivalent. Several other operations are used to refer the variables to the system power base SBASE instead of the machine power base MBASE:

```
C
C     MODE = 1 => INITIAL CONDITIONS
C
 100  CONTINUE
      VDIP = ISORCE(MC)*ZSORCE(MC)*
     &MBASE(MC)/SBASE
      VAR(L+0) = REAL(VDIP)
```

```
      VAR(L+1) = AIMAG(VDIP)
      IBUS = ISORCE(MC)*SBASE/MBASE(MC) -
     &VOLT(IB)/ZSORCE(MC)
      PELEC(MC) =  real(VOLT(IB)*
     &conjg(ibus))*MBASE(MC)/SBASE
      QELEC(MC) = aimag(VOLT(IB)*
     &conjg(ibus))*MBASE(MC)/SBASE
      ETERM(MC) = abs(VOLT(IB))
      return
```

No calculation is performed at the second entry point, since there are not state variables in the model:

```
C
C     MODE = 2 => RATE OF CHANGE OF THE
C                 STATE VARIABLES
C
 200  continue
      return
```

At the third entry point the value of the voltage VDIP is calculated as a function of the time. This is the part of the model where the shape of the voltage dip is imposed. Here the voltage dip begins at time TIME = 1 second.

```
C
C     MODE = 3 => VDIP AND OUTPUT VARIABLES
C                 CALCULATION
C
 300  continue
      IF (TIME.LT.1.0) THEN
         VDIP = VAR(L+0)+jay*VAR(L+1)
      ENDIF
      IF (TIME.GE.1.0).AND.(TIME.LT.1.5) THEN
         VDIP = (VAR(L+0)+jay*VAR(L+1))
     &    /ABS(VAR(L+0)+jay*VAR(L+1))*0.2
      ENDIF
      IF (TIME.GE.1.5).AND.(TIME.LT.2.0) THEN
         VDIP = (VAR(L+0)+jay*VAR(L+1))
     &    /ABS(VAR(L+0)+jay*VAR(L+1))
     &    *(0.2+(TIME-1.5)*1.2)
      ENDIF
      IF (TIME.GE.2.0).AND.(TIME.LT.16.0) THEN
         VDIP = (VAR(L+0)+jay*VAR(L+1))
     &    /ABS(VAR(L+0)+jay*VAR(L+1))
     &    *(0.8+(TIME-2.0)*0.15/14)
      ENDIF
      IF (TIME.GE.16.0) THEN
         VDIP = (VAR(L+0)+jay*VAR(L+1))
     &    /ABS(VAR(L+0)+jay*VAR(L+1))*0.95
      ENDIF
      ISORCE(MC) = VDIP/ZSORCE(MC)
     &*MBASE(MC)/SBASE
      ibus = ISORCE(MC)*SBASE/MBASE(MC) -
     & VOLT(IB)/ZSORCE(MC)
      PELEC(MC) =  real(VOLT(IB)*conjg(ibus))
     &*MBASE(MC)/SBASE
      QELEC(MC) = aimag(VOLT(IB)*conjg(ibus))
     &*MBASE(MC)/SBASE
      ETERM(MC) = abs(VOLT(IB))
return
```

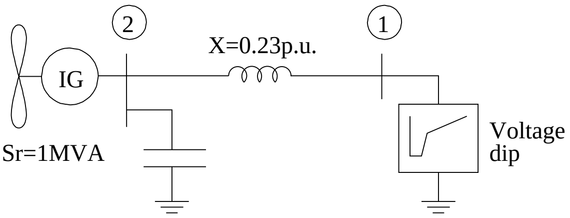

Fig. 2. Case including the windmill and the voltage dip

IV. EXAMPLE OF APPLICATION

The voltage dip model has been applied to the base case shown in fig. 2 in order to study the response of a typical fixed-speed windmill to the dip. The case consists of two buses. Bus number one represents the grid, while the windmill is connected at bus number two. Both buses are connected through a reactance which accounts for the effect of every transformer and line between the generator and the grid. This reactance is 0.12 p.u. on a 1 MVA, 0.69 kV base.Losses in the circuit are neglected.

The value of the reactance has been calculated supposing that there exists a 0.69kV/20kV transformer connected to the windmill with a short-circuit reactance of 0.07 p.u., and that the short-circuit power at the connection point is 20 times the rated power of the windmill, this is, a short-circuit reactance of 0.05 p.u.. The value of the short-circuit power is a minimum currently imposed by the Spanish law for wind power installations.

Several capacitors are connected to the induction generator in order to compensate the reactive power consumption. It has been supposed that the size of the capacitors is such that the windmill together with them operates at unity power factor.

IV-A. Fixed-speed windmill model

A typical indiction generator model for transient stability studies, which neglects stator transients and with one rotor winding, has been used. The equations of the generator model, taking positive currents going out from the machine, are [5], [6]:

$$\frac{dv'_d}{dt} = -\frac{1}{T'_o}[v'_d - (X_s - X'_s)i_{qs}] + js\omega_{base}v'_q \tag{1}$$

$$\frac{dv'_q}{dt} = -\frac{1}{T'_o}[v'_q + (X_s - X'_s)i_{ds}] - js\omega_{base}v'_d \tag{2}$$

$$\tau_{em} = v'_d i_{ds} + v'_q i_{qs} \tag{3}$$

where the subindexes d, q stand for the voltage and current components aligned with the d, q axis in the synchronous rotating reference frame and s is the slip. This model represents the generator as a internal voltage $v'_d + jv'_q$ behind a transient reactance $R_s + jX'_s$. Parameters T'_o and X'_s are calculated as $T'_o = X_r/R_r$ and

$X'_s = X_s - X_m^2/X_r$. All variables are in per unit but the rated frequency ω_{base}, which is in radians per second.

The electric parameters of the machine R_s, X_s, Xm, R_r and X_r stand for the stator resistance and reactance, mutual reactance and rotor resistance and reactance, respectively, are shown in section I.

The windmill drive train is modelled by two lumped masses, which represent the low-speed shaft (blades, hub) and the high speed shaft (rotor of the generator). Both masses are linked through a flexible coupling. The equations of the model are:

$$\frac{d\theta_{tg}}{dt} = \omega_g - \omega_t \qquad (4)$$

$$\frac{d\omega_t}{dt} = \frac{1}{2H_t}(\tau_{wind} + K\theta_{tg} + D(\omega_g - \omega_t)) \qquad (5)$$

$$\frac{d\omega_g}{dt} = \frac{1}{2H_g}(-\tau_{em} - K\theta_{tg} - D(\omega_g - \omega_t)) \qquad (6)$$

where θ_{tg} is the angle between the turbine and the generator, ω_t, ω_g, H_t and H_g are the turbine and generator frequencies and inertia constants, respectively, K and D are the drive train stiffness and damping constants, τ_{wind} is the torque provided by the wind and τ_{em} is the electromagnetic torque. All parameters are in per unit. Input torque τ_{wind} is assumed constant during the simulations [7]. The mechanical parameters used in the simulations are shown in section I.

V. SIMULATIONS

Several simulations have been performed in order to estimate the maximum amount of active power provided by the windmill which result in a stable case. It has been obtained that, with the windmill generating 0.9 MW the windmill is not able to return to the rated speed, and thus the case is unstable. With the windmill generating 0.85 MW, the case is stable.

The following figures show the trajectories of several variables at the critically stable case, this is, when the voltage dip is applied to the windmill providing 0.85 MW. Fig. 3 shows the voltage at buses one and two. Voltage at bus one follows exactly the pattern described by fig. 1, as it is imposed by the voltage dip model. Voltage at bus two, where the windmill is connected, oscillates under the voltage dip value prior to stabilising, following the rotor oscillations in the generator.

Fig. 4 and fig. 5 show the active and reactive power input at bus two, respectively. It may be seen that the active power suffers large oscillations during several seconds before returning again at the initial value. On the other hand, the reactive power output, which begins at zero due to the capacitors, decays to negative values during the voltage dip. This means that the induction generator is consuming reactive power on order to recover magnetisation when the voltage recovers. This consumption of reactive power results in the voltage oscillations observed in fig. 3.

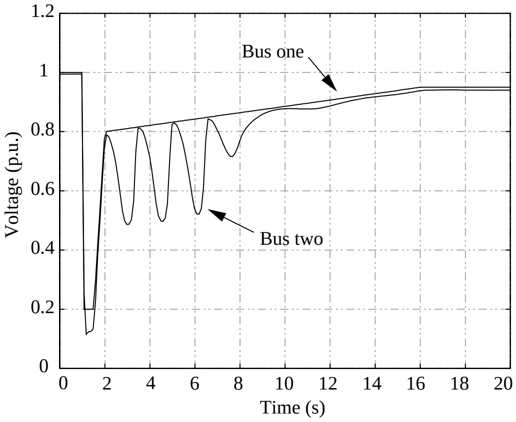

Fig. 3. Voltage at bus one and two

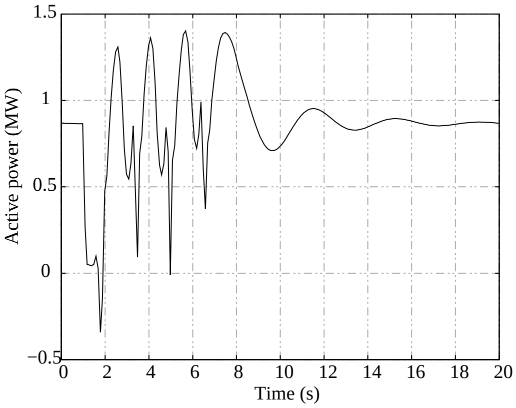

Fig. 4. Active power output.

Fig. 6 show the rotor speed during the simulation. Rotor speed reflects the presence of two modes of oscillation as a result of the presence of two masses. The oscillations due to the low-speed shaft are larger and slower, while the oscillations due to the high-speed shaft are smaller and faster.

VI. CONCLUSION

Two are the main results of this work:

- A model of a voltage dip has been developed in power system simulation tool PSS/E.
- The performance of the model has been tested with good results at a simple case.

APPENDIX I
PARAMETERS

Tables I to III show the relevant parameters of the study.

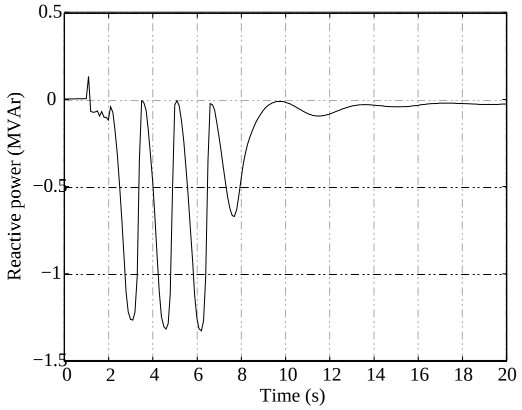

Fig. 5. Reactive power output.

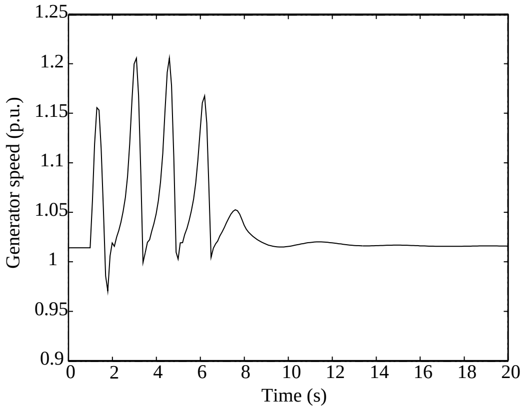

Fig. 6. Rotor speed.

Parameter	Value	Units
Low speed inertia constant H_t	5	s
High speed inertia constant H_g	0.5	s
Stiffness K	30	p.u.
Damping D	0	p.u.

TABLE I

WINDMILL DRIVE TRAIN

Parameter	Value	Units
Rated power	1	MVA
Rated voltage	0.69	kV
Stator resistance R_s	0.01	p.u.
Stator leakage inductance X_s	0.1	p.u.
Mutual inductance X_m	4.6	p.u.
Rotor resistance R_r	0.015	p.u.
Rotor leakage inductance X_r	0.05	p.u.

TABLE II

WINDMILL INDUCTION GENERATOR

ACKNOWLEDGMENT

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Parameter	Value	Units
Base power	1	MVA
Base voltage	0.69	kV
1-2 line reactance	0.12	p.u.

TABLE III

GRID

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