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ACTIVE AND REACTIVE POWER CONTROL OF WIND TURBINE DRIVEN DFIG

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ABSTRACT
This paper first introduces the double-fed wind power generation system's basic theory, and builds the mathematical model of the double-fed generator in the rotary coordinate system. In order to deal with the strong coupling problems in motor control field, the motor vector control technology is researched and the idea of dual-fed generator stator-flux-oriented vector control strategy is presented by application of vector control. Based on that theory and the characteristics of double-fed generators' grid-connected power control, a dual-channel and double-loop control method with current inner-loop and power outer-loop is presented[1]. In Matlab /Simulink environment, the simulation results show that the control strategy can achieve the decoupling of the active power and reactive power in double-fed power generation system.

Keywords: Wind energy generation; stator-flux-oriented control strategy; dual-channel and do.

I. INTRODUCTION

With increased penetration of wind power into electrical grids, DFIG wind turbines are largely deployed due to their variable speed feature and hence influencing system dynamics. This has created an interest in developing suitable models for DFIG to be integrated into power system studies. The continuous trend of having high penetration of wind power, in recent years, has made it necessary to introduce new practices. For example, grid codes are being revised to ensure that wind turbines would contribute to the control of voltage and frequency and also to stay connected to the host network following a disturbance. In response to the new grid code requirements, several DFIG models have been suggested recently, including the full-model which is a 5th order model. These models use quadrature and direct components of rotor voltage in an appropriate reference frame to provide fast regulation of voltage. The 3rd order model of DFIG which uses a rotor current, not a rotor voltage as control parameter can also be applied to provide very fast regulation of instantaneous currents with the penalty of losing accuracy. Apart from that, the 3rd order model can be achieved by neglecting the rate of change of stator flux linkage (transient stability model), given rotor voltage as control parameter. Additionally, in order to model back-to back PWM converters, in the simplest scenario, it is assumed that the converters are ideal and the DC-link voltage between the converters is constant. Consequently, depending on the converter control, a controllable voltage (current) source can be implemented to represent the operation of the rotor-side of the converter in the model. However, in reality DC-link voltage does not keep constant but starts increasing during fault condition. Therefore, based on the above assumption it would not be possible to determine whether or not the DFIG will actually trip following a fault. In order to resolve the identified problems, a switch-by-switch model of voltage-fed, current controlled PWM converters, where triangular carrier-based Sinusoidal PWM (SPWM) is applied to maintain the switching frequency constant. In order to achieve constant switching frequency, calculation of the required rotor voltage that must be supplied to the generator is adopted. Various methods such as hysteresis controller, stationary PI controller and synchronous PI controller have been adopted in order to control current-regulated induction machine. Among which, synchronous PI controller has been acknowledged as being superior.. It is not clear what are the long term consequences of using the DFIG for harmonic and reactive power compensation. some researchers believe that the DFIG should be used only for the purpose for which it has been installed, i.e., supplying active power only.

II. DOUBLY FED INDUCTION GENERATOR

Wind turbines use a doubly-fed induction generator (DFIG) consisting of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter. The stator winding is connected directly to the 50 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter. The DFIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind. The optimum turbine speed producing maximum mechanical energy for a given wind speed is proportional to the wind speed. Another advantage of the DFIG technology is the ability for power electronic converters to generate or absorb reactive power, thus eliminating the need for installing capacitor banks as in the case of squirrel-cage induction generator.

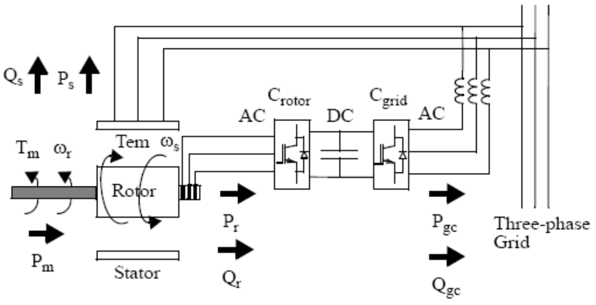
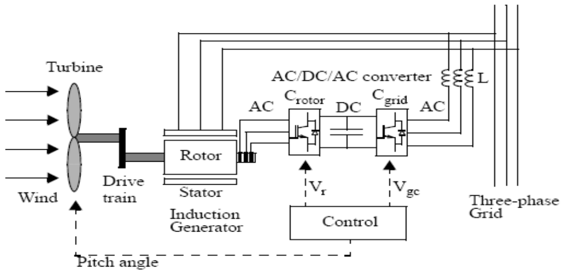


Fig.-1 basic diagram of Doubly fed induction generator with converters

Where Vr is the rotor voltage and Vgc is grid side voltage. The AC/DC/AC converter is basically a PWM converter which uses sinusoidal PWM technique to reduce the harmonics present in the wind turbine driven DFIG system. Here Crotor is rotor side converter and Cgrid is grid side converter. To control the speed of wind turbine gear boxes or electronic control can be used.



Operating Principle of DFIG

Fig. 2.2 Power flow diagram of DFIG

The stator is directly connected to the AC mains, whilst the wound rotor is fed from the Power Electronics Converter via slip rings to allow DIFG to operate at a variety of speeds in response to changing wind speed. Indeed, the basic concept is to interpose a frequency converter between the variable frequency induction generator and fixed frequency grid. The DC capacitor linking stator- and rotor-side converters allows the storage of power from induction generator for further generation. To achieve full control of grid current, the DC-link voltage must be boosted to a level higher than the amplitude of grid line-to-line voltage. The slip power can flow in both directions, i.e. to the rotor from the supply and from supply to the rotor and hence the speed of the machine can be controlled from either rotor- or stator-side converter in both super and sub-synchronous speed ranges. As a result, the machine can be controlled as a generator or a motor in both super and sub-synchronous operating modes realizing four operating modes. Below the synchronous speed in the motoring mode and above the synchronous speed in the generating mode, rotor-side converter operates as a rectifier and stator-side converter as an inverter, where slip power is returned to the stator. Below the synchronous speed in the generating mode and above the synchronous speed in the motoring mode, rotor-side converter operates as an inverter and statorside converter as a rectifier, where slip power is supplied to the rotor. At the synchronous speed, slip power is taken from supply to excite the rotor windings and in this case machine behaves as a synchronous machine. The mechanical power and the stator electric power output are computed as follows:

$$P_r = T_m * \omega_r$$

$$P_s = T_{em} * \omega_s$$

For a loss less generator the mechanical equation is:

$$J\frac{d\omega_r}{dt} = T_m - T_{em}$$

In steady-state at fixed speed for a loss less generator

$$T_m = T_{em} \;\&\; P_m = P_s + P_r$$

and It follows that:

$$P_r = P_m - P_s = T_m\omega_r - T_{em}\omega_s = -sP_s$$

where

$$s = (\omega_s - \omega_r)/\,\omega_s$$

is defined as the slip of the generator

Generally the absolute value of slip is much lower than 1 and, consequently, Pr is only a fraction of Ps. Since Tm is positive for power generation and since ωs is positive and constant for a constant frequency grid voltage, the sign of Pr is a function of the slip sign. Pr is positive for negative slip (speed greater than synchronous speed) and it is negative for positive slip (speed lower than synchronous speed). For supersynchronous speed operation, Pr is transmitted to DC bus capacitor and tends to rise the DC voltage. For sub-synchronous speed operation, Pr is taken out of DC bus capacitor and tends to decrease the DC voltage. Cgrid is used to generate or absorb the power Pgc in order to keep the DC voltage constant. In steady-state for a lossless AC/DC/AC converter Pgc is equal to Pr and the speed of the wind turbine is determined by the power Pr absorbed or generated by Crotor. The phase-sequence of the AC voltage generated by Crotor is positive for sub-synchronous speed and negative for supersynchronous speed. The frequency of this voltage is equal to the product of the grid frequency and the absolute value of the slip. Crotor and Cgrid have the capability for generating or absorbing reactive power and could be used to control the reactive power or the voltage at the grid terminals.

III. DYNAMIC SIMULATION OF DFIG IN TERMS OF DQ-WINDING

The general model for wound rotor induction machine is similar to any fixed-speed induction generator as follows :

1. Voltage equations:

Stator Voltage Equations:

$$V_{qs} = p\lambda_{qs} + \omega\lambda_{qs} + r_s i_{qs}$$
$$V_{ds} = p\lambda_{ds} - \omega\lambda_{ds} + r_s i_{ds}$$

Rotor Voltage Equations:

$$V_{qr} = p\lambda_{qr} + (\omega - \omega_r)\omega\lambda_{dr} + r_r i_{qr}$$
$$V_{dr} = p\lambda_{dr} - (\omega - \omega_r)\omega\lambda_{qr} + r_r i_{qr}$$

2. Power Equations:

$$P_s = -3/2(v_{ds}i_{ds} + v_{qs}i_{qs})$$
$$Q_s = -3/2(v_{qs}i_{qs} + v_{ds}i_{ds})$$

3. Torque Equation:

$$T_g = -3P/4\,(\lambda_{ds}i_{qs} - \lambda_{qs}i_{ds})$$

4. Flux Linkage Equations:

Stator Flux Equations:

$$\lambda_{qs} = (L_{ls} + L_m)i_{qs} + L_m i_{qr}$$
$$\lambda_{ds} = (L_{ls} + L_m)i_{ds} + L_m i_{dr}$$

Rotor Flux Equations:

$$\lambda_{qr} = (L_{lr} + L_m)i_{qr} + L_m i_{qs}$$
$$\lambda_{dr} = (L_{lr} + L_m)i_{dr} + L_m i_{ds}$$

IV. MODELING OF DFIG WIND TURBINE

DFIG wind turbines use a wound rotor induction generator,where the rotor winding is fed through a back-to-back variable frequency PWM converter as shown in Fig. 1 [10]–[13]. Voltage limits and an over-current “crowbar” circuit protect the machine and converters. The converter system enables the two-way transfer of power.Converter 2 (C2) is fed from the generator stator terminals via a reactive link and provides a dc supply to Converter 1 (C1) that produces a variable frequency three-phase supply to the generator rotor via slip rings. The frequency of the rotor supply is controlled so that under steady conditions, the combined speed of the rotor plus the rotational speed of the rotor ux vector matches that of the synchronously rotating stator ux vector fixed by the network frequency. In terms of this form of representation, adjustment of the axes components of the rotor voltage provides the capability In this paper, a DFIG third-order model with respect to the frame is used to represent the wind turbine. This facilitates a good compromise between simplicity and accuracy [3], [17].

V. CONVERTER CONTROL SYSTEM

The back to back PWM converter has two converters, one is connected to rotor side and another is connected to grid side. Control by both converters has been discussed here,

6.1 Rotor side converter Control System

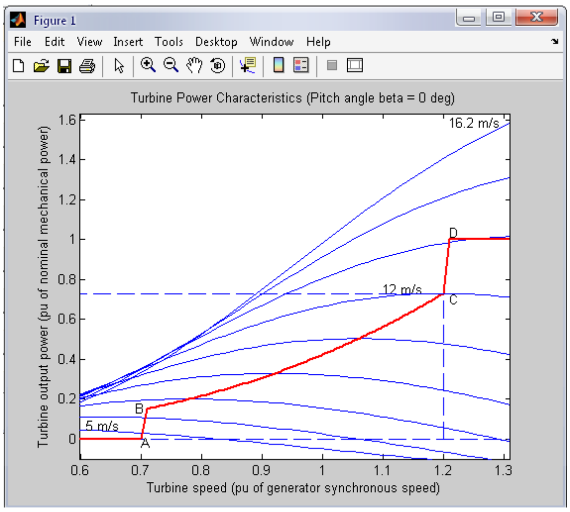


Figure - Turbine power characteristics

The rotor-side converter is used to control the wind turbine output power and the voltage measured at the grid terminals. The power is controlled in order to follow a pre-defined power-speed characteristic, named tracking characteristic. This characteristic is illustrated by the ABCD curve superimposed to the mechanical power characteristics of the turbine obtained at different wind speeds. The actual speed of the turbine ωr is measured and the corresponding mechanical power of the tracking characteristic is used as the reference power for the power control loop. The tracking characteristic is defined by four points: A, B, C and D. From zero speed to speed of point A the reference power is zero. Between point A and point B the tracking characteristic is a straight line. Between point B and point C the tracking characteristic is the locus of the maximum power of the turbine (maxima of the turbine power vs turbine speed curves). The tracking characteristic is a straight line from point C and point D. The power at point D is one per unit.

Beyond point D the reference power is a constant equal to one per unit

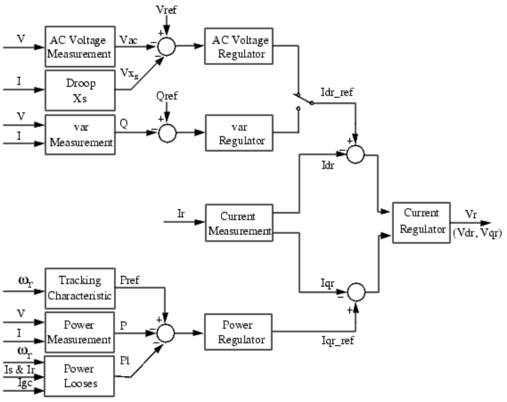


Fig Rotor converter control block

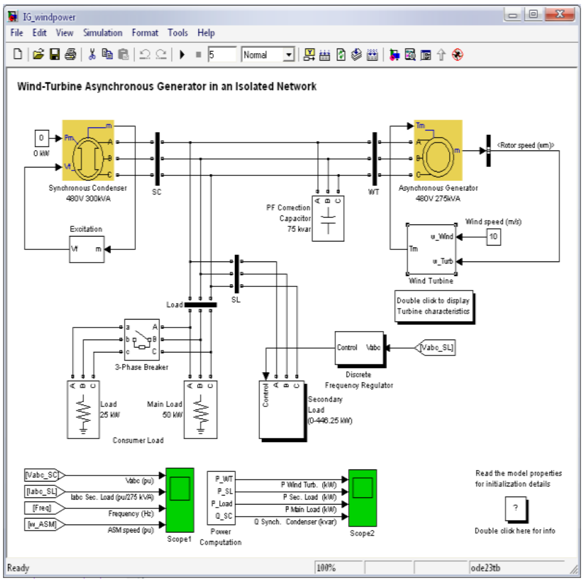
Diagram For the rotor-side controller the d-axis of the rotating reference frame used for d-q transformation is aligned with air-gap flux. The actual electrical output power, measured at the grid terminals of the wind turbine, is added to the total power losses (mechanical and electrical) and is compared with the reference power obtained from the tracking characteristic. A Proportional-Integral (PI) regulator is used to reduce the power error to zero. The output of this regulator is the reference rotor current Iqr_ref that must be injected in the rotor by converter Crotor. This is the current component that produces the electromagnetic torque Tem. The actual Iqr component is compared to Iqr_ref and the error is reduced to zero by a current regulator (PI). The output of this current controller is the voltage Vqr generated by Crotor.

6.2 Grid side converter control system

The Grid side converter is used to regulate the voltage of the DC bus capacitor. For the grid-side controller the d-axis of the rotating reference frame used for d-q transformation is aligned with the positive sequence of grid voltage. This controller consists of:

[1] A measurement system measuring the d and q components of AC currents to be controlled as well as the DC voltage Vdc.
[2] An outer regulation loop consisting of a DC voltage Regulator.
[3] An inner current regulation loop consisting of a current Regulator.

The current regulator controls the magnitude and phase of the voltage generated by converter Cgrid (Vgc) from the Idgc_ref produced by the DC voltage regulator and specified Iq_ref reference.



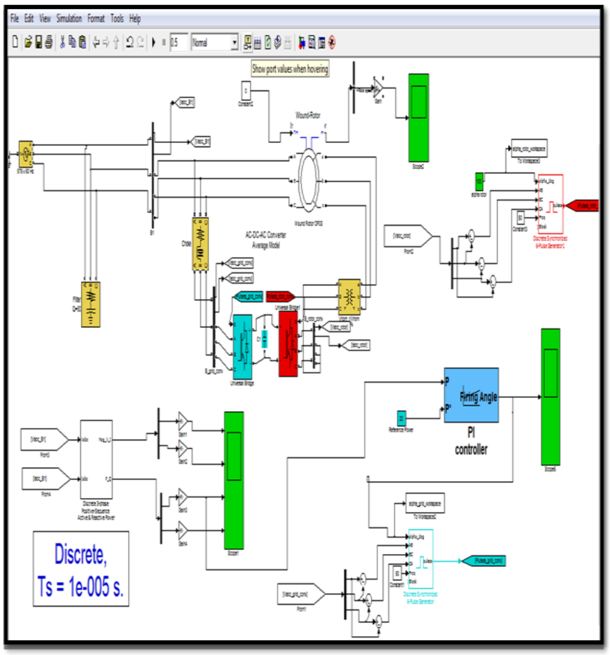
The current regulator is assisted by feed forward terms which predict the Cgrid output voltage.

VI. WIND TURBINE DRIVEN ISOLATED INDUCTION GENERATOR MODEL SIMULATION IN SIMULINK

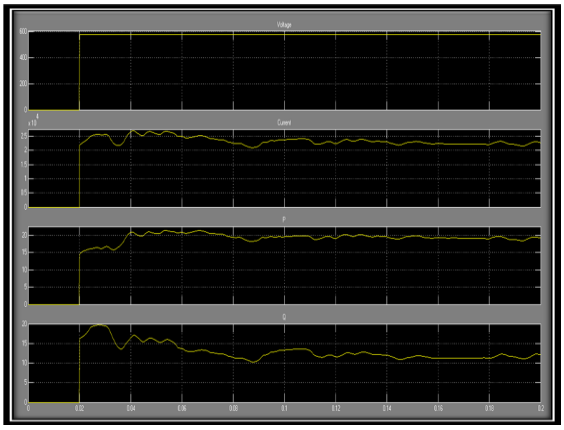
Operation of Induction Generators (IG) Driven by Variable-Pitch Wind Turbines. A wind farm consisting of six 1.5-MW wind turbines is connected to a 25-kV distribution system exports power to a 120-kV grid through a 25-km 25-kV feeder. The 9-MW wind farm is simulated by three pairs of 1.5 MW wind-turbines. Wind turbines use squirrel-cage induction generators (IG). The stator winding is connected directly to the 50 Hz grid and the rotor is driven by a variablepitch wind turbine. The pitch angle is controlled in order to limit the generator output power at its nominal value for winds exceeding the nominal speed (9 m/s). In order to generate power the IG speed must be slightly above the synchronous speed. Speed varies approximately between 1 pu at no load and 1.005 pu at full load. Each wind turbine has a protection system monitoring

voltage, current and machine speed. Reactive power absorbed by the IGs is partly compensated by capacitor banks connected at each wind turbine low voltage bus (400 kvar for each pair of 1.5 MW turbine) and the rest of reactive power required to maintain the 25-kV voltage at bus B25 close to 1 pu is provided by a 3-Mvar STATCOM with a 3% droop setting.

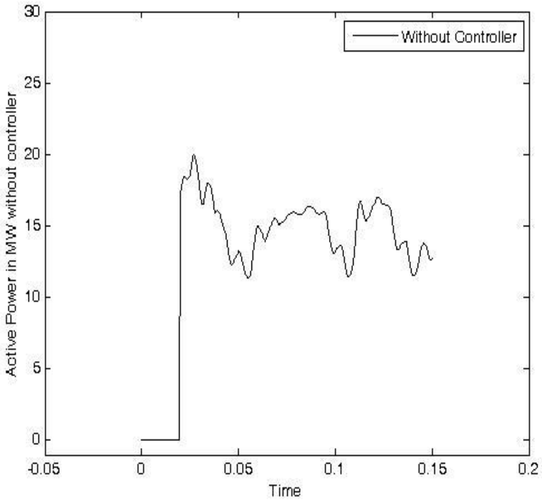
1.1 Matlab simulation and its Output Characteristics

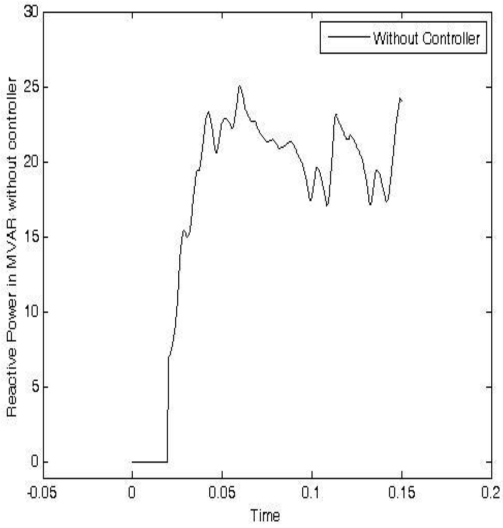


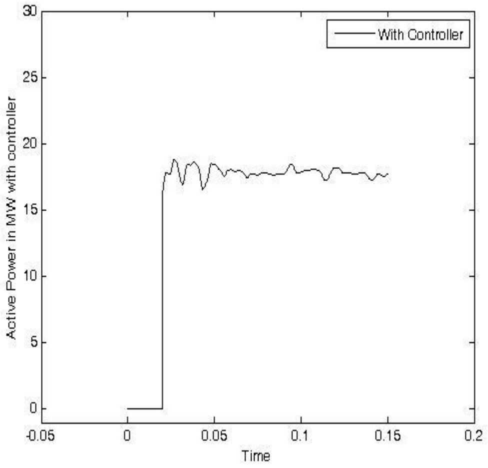
OUTPUT:- Vabc, Iabc, P , Q respectively,

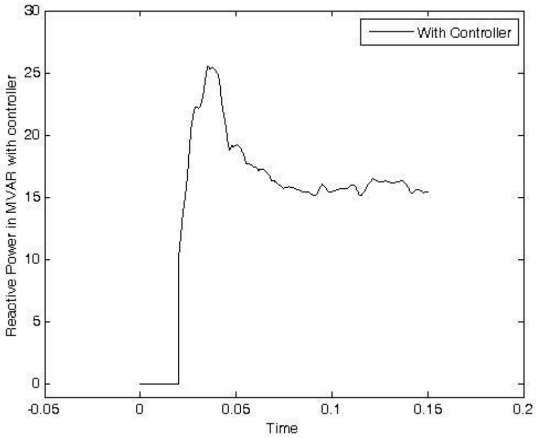


1.2 Output Characteristics of DFIG With and Without PI controller

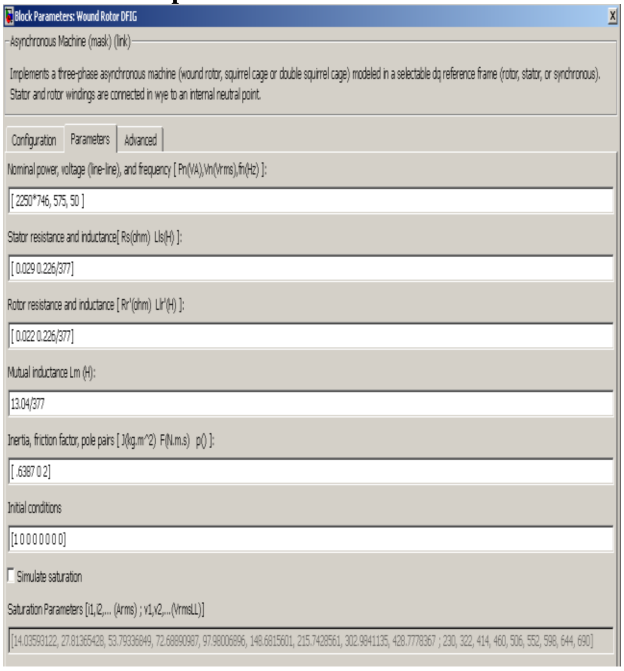








1. Block parameters of DFIG:



Implements a three-phase asynchronous machine (wound rotor, squirrel cage or double squirrel cage) modeled in a selectable dq reference frame (rotor, stator, or synchronous). Stator and rotor windings are connected in wye to an internal neutral point.

Nominal power, voltage (line-line), and frequency [Pn(VA),Vn(Vrms),fn(Hz)]:
[2250*746, 575, 50]

Stator resistance and inductance[Rs(ohm) Lls(H)]:
[0.029 0.226/377]

Rotor resistance and inductance [Rr'(ohm) Llr'(H)]:
[0.022 0.226/377]

Mutual inductance Lm (H):
13.04/377

Inertia, friction factor, pole pairs [J(kg.m^2) F(N.m.s) p()]:
[.6387 0 2]

Initial conditions
[1 0 0 0 0 0 0 0]

☐ Simulate saturation

Saturation Parameters [i1,i2,... (Arms) ; v1,v2,...(VrmsLL)]
[14.03593122, 27.81365428, 53.79336849, 72.68890987, 97.98006896, 148.6815601, 215.7428561, 302.9841135, 428.7778367 ; 230, 322, 414, 460, 506, 552, 598, 644, 690]

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