THE APPLICATION OF USER DEFINED INDUCTION MACHINE MODELS IN EMTP

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Abstract: New developments in the user–defined modeling facility MODELS in the ATP version of EMTP allow the simultaneous solution of linear and non–linear differential and algebraic equations within a user defined model, as well as the simultaneous solution and interface between a user defined model and the electrical network. One application of interest, supported by the Bonneville Power Administration (BPA) is the modeling of induction motors in transmission system performance studies. As an example, the paper presents the simultaneous equations of a symmetrical induction motor described in MODELS, where the motor equations are iteratively solved at the same time as the electrical network solution. The paper demonstrates the use of the new type–94 interface between MODELS and the electrical network.

Keywords: EMTP, ATP, MODELS, type–94, induction motor

I. INTRODUCTION

The capability to develop a user defined model in the Alternative Transient Program (ATP) version of EMTP has been further expanded due to recent developments in the MODELS solver and its iterface with ATP. Within MODELS, any set of linear and nonlinear and algebraic equations can be solved simultaneously within a model, and simultanoeously with the circuit solution of ATP. As a demonstration, the paper presents the simultaneous equations of a symmetrical induction motor using MODELS, where the motor equations are iteratively solved at the same time as the electrical network solution. The paper illustrates the induction motor performance solved in MODELS during a motor start up and a load torque step change for a running motor connected to a transmission network. Multiple instances of the same induction motor model can be used in an application.

II. DISCUSSION

As power quality issues rise, there is a growing need to study the impact of induction motor transients on voltage sensitive customers. Startup of a large induction motor in a weak system can cause large voltage dips for several seconds, potentially effecting voltage sensitive manufacturing processes.

Transient voltage instability can be caused by a group of induction motors following a power system disturbance if they fail to accelerate back to rated speed. The voltage depression can cause the motor to draw large current that in turn, can damage motor windings.

Outstanding motor protection issues such as faults within the induction motor are discussed briefly in section VIII. CONCLUSIONS.

III. MOTOR IMPLEMENTATION USING ATP–MODELS

To evaluate system performance, the transmission network including the dynamic loads like induction motors must be modeled adequately. Up to now, an induction motor, such as the 2300V, 2500hp induction motor described in this paper, could be modeled in EMTP/ATP program as a Universal Machine type–19 (UM–19) [1,2]. A creative use of the UM–19 model is presented in [2], which uses a double–cage representation of the rotor windings to account for the eddy current effects the saturation of rotor and stator inductances.

Although a powerful tool for modeling the rotating electric machinery, the UM models are limited. For example, the UM models do not provide a capability for the user to place an internal fault within the stator or rotor windings.

The recent development in the MODELS solver and the type–94 interface between MODELS and ATP provides the user more flexibility to represent, a user defined model, the operation of arbitrary circuit components and to include the operation of these models simultaneously with the solution of the rest of the ATP transmission network.

IV. INDUCTION MOTOR MODEL

The induction motor is modeled according to the solution model presented in [3] and shown in Figure 1.

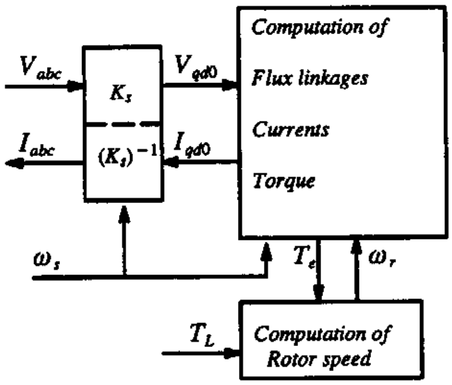

Figure 1. Induction Motor Computer Model

The electrical inputs are the three–phase *abc* voltages at the induction motor stator terminal $(V_a V_b V_c)$. The outputs are three–phase *abc* currents into the stator $(I_a I_b I_c)$.

In ATP, the machine equations are solved in the *dq*0 synchronous reference frame (*d* – direct axis of rotor, *q* – quadrature axis of rotor, 0 – zero sequence). The phase V_{abc} voltages are converted from phase to the *dq*0 domain V_{dqo} using Park's transformation.

Flux linkages per second for the stator (ψ_{ds} , ψ_{qs} , ψ_{0s}) and the rotor (ψ_{dr} , ψ_{qr} , ψ_{0r}) and rotor angular speed ω_r are used as the model state variables. The $dq0$ domain I_{dq0} currents are computed from the flux linkages and then converted back to the I_{abc} phase domain using inverse Park's transformation.

Since the time constants of mechanical rotor dynamics are significantly larger than the time constants of the electromagnetic characteristics, their solutions can be performed sequentially. The flux equations are solved simultaneously first, assuming constant speed, and the rotor speed is computed next using the electromagnetic torque. The rotor speed in turn is used to update the coefficients to be used in the flux equation at the next model execution. This decoupling of the solution reduces the size of the silmultaneous set of equations, allowing faster execution and easier convergence of the iteration, without significant loss of accuracy.

A. Linear Flux Equations

The equations for simulating an induction machine may be established first, by solving the following flux linkage equations in [3]:

$$\psi_{ds} = \frac{\omega_s}{p}[v_{ds} + \frac{\omega}{\omega_s}\psi_{qs} + \frac{r_s}{X_{ls}}(\psi_{md} - \psi_{ds})] \tag{1}$$

$$\psi_{qs} = \frac{\omega_s}{p}[v_{qs} - \frac{\omega}{\omega_s}\psi_{ds} + \frac{r_s}{X_{ls}}(\psi_{mq} - \psi_{qs})] \tag{2}$$

$$\psi_{0s} = \frac{\omega_s}{p}[v_{0s} - \frac{r_s}{X_{ls}}\psi_{0s}] \tag{3}$$

and

$$\psi'_{dr} = \frac{\omega_s}{p}[+\frac{\omega - \omega_r}{\omega_s}\psi'_{qr} + \frac{r'_s}{X'_{lr}}(\psi_{md} - \psi'_{dr})] \tag{4}$$

$$\psi'_{qr} = \frac{\omega_s}{p}[-\frac{\omega - \omega_r}{\omega_s}\psi'_{dr} + \frac{r'_s}{X'_{lr}}(\psi_{mq} - \psi'_{qr})] \tag{5}$$

$$\psi'_{0r} = \frac{\omega_s}{p}[-\frac{r'_s}{X'_{ls}}\psi'_{0r}] \tag{6}$$

The flux linkage equations in turn are used to solve the current equations:

$$i_{ds} = \frac{1}{X_{ls}}(\psi_{ds} - \psi_{md}) \tag{7}$$

$$i_{qs} = \frac{1}{X_{ls}}(\psi_{qs} - \psi_{mq}) \tag{8}$$

$$i_{0s} = \frac{1}{X_{ls}}(\psi_{0s}) \tag{9}$$

$$i'_{dr} = \frac{1}{X'_{lr}}(\psi'_{dr} - \psi_{md}) \tag{10}$$

$$i'_{qr} = \frac{1}{X'_{lr}}(\psi'_{qr} - \psi_{mq}) \tag{11}$$

$$i'_{0r} = \frac{1}{X'_{lr}}(\psi'_{0r}) \tag{12}$$

where

$$\psi_{mq} = X_M\ (i_{qs} + i'_{qr}) \tag{13}$$

$$\psi_{md} = X_M\ (i_{ds} + i'_{dr}) \tag{14}$$

Electrical torque is computed using the motor fluxes.

$$T_e = \psi_{ds}i_{qs} - \psi_{qs}i_{ds} \tag{15}$$

The difference between electrical and mechanical (can be speed dependent) torque enters the speed equation.

$$\omega_r = \frac{\omega_s}{2Hp}(T_e - T_L) \tag{16}$$

The induction motor saturation is neglected. The set of flux, current and torque equations 1-16 require simultaneous solutions in parallel, within a single time step. In the new ATP-MODELS, data file (*.dat file) this is implemented by using a linear COMBINE statement, as shown in TABLE I.

TABLE I.

```
EXEC
 — Park's Transformation
{ — slove for VD,VQ,VO using VA, VB, VC }
 — Solving  Coefficients
 — DQ Axes
 COMBINE AS FLUX
 — Magnetizing Flux (equations 13–14):
  PSIMQ :- SUM( XMlCQS + XMlCQR )
  PSIMD :- SUM( XMlCDS + XMlCDR )
 — Currents (equations 7–8, 10–11):
  CDS :- SUM ( (1/XLS)lPSIDS – (1/XLS)lPSIMD )
  CQS :- SUM ( (1/XLS)lPSIQS – (1/XLS)lPSIMQ )
  CQR :- SUM ( (1/XR) lPSIQR – (1/XR) lPSIMQ )
  CDR :- SUM ( (1/XR) lPSIDR – (1/XR) lPSIMD )
  — Winding Fluxes (equations 1–2, 4–5):
PSIDSPR :- SUM( VDl + 1.lPSIQS + (RS/XLS)lPSIMD – (RS/XLS)lPSIDS )
PSIQRPR :- SUM( (WR/WS–1.)lPSIDR + (RR/XR)lPSIMQ –
(RR/XR)lPSIQR )
PSIDRPR :- SUM( (1.–WR/WS)lPSIQR + (RR/XR)lPSIMD –
(RR/XR)lPSIDR )
PSIQSPR :- SUM( VQl – 1.lPSIDS + (RS/XLS)lPSIMQ – (RS/XLS)lPSIQS )
   — Differential Equations for Flux:
CLAPLACE(PSIQS/PSIQSPR):-(WSls0)/(1.ls1+0.ls0)
CLAPLACE(PSIQR/PSIQRPR):-(WSls0)/(1.ls1+0.ls0)
CLAPLACE(PSIDS/PSIDSPR):-(WSls0)/(1.ls1+0.ls0)
CLAPLACE(PSIDR/PSIDRPR) :- (WSls0)/(1.ls1+0.ls0)
ENDCOMBINE
   — 0 Sequence Axis (equation 3):
PSIOSPR:- SUM ( 1.lVO – (RS/XLS)lPSIOS)
CLAPLACE(PSIOS/PSIOSPR) :- (WSls0)/(1.ls1+0.ls0)
CO :- 1/XLS*PSIOS
 —  Mechanical system
TE :- ( PSIDS*CQS – PSIQS*CDS )*(3/2)*(PP/2)*(1/WS)
SLIP :- ( WS – WR )/WS
TL :- 0.0
DT :- (TE – TL)*PP/JJ/2.
CLAPLACE(WR/DT) :- (1.ls0)/(1.ls1+0.ls0)
 — Inverse Park's Transformation:
 — Solve for CA, CB, CC using CD, CQ, C0
```

The glossary of terms in TABLE I. is shown in section IX.

B. Motor Models and Transmission Network Interface

The induction motor is represented in the ATP using a type–94 nonlinear circuit component in iterated mode. The model inputs are the three–phase voltages at the motor terminals. The model outputs are three–phase currents into the motor and the transfer conductances matrix of the model. The transfer conductance values are used by the Newton iteration routine of ATP, used for finding a solution point for the nonlinear components of the circuit at each time step.

Each value of the transfer conductance matrix is the present value of the derivative of each current with respect to each phase voltage of the motor. Instead of calculating these values at each iteration of each time step, constant values are used. This results in a few more Newton iterations on the circuit side of the solution, but is overall less costly. The motor connection to the transmission network is shown in TABLE II. as a three–phase, iterated type–94 component.

TABLE II.

```
C — electric network branch
C —Motor Connection to the Network
94MOT1X  MOTOR ITER
94MOT1Y
94MOT1Z
>DATA  XLS   0.226ohm { stator leakage reactance, ohms
>DATA  RS    0.029    { stator resistance, ohms
>DATA  XR    0.226    { rotor leakage reactance, ohms
>DATA  RR    0.022    { rotor resistance, ohms
>DATA  XM    13.04    { magnetizing reactance, ohms
>DATA  JJ    63.87    { inertia, kg-m2
>DATA  PP    4.       { number of poles
>SSV   MOT1X
>SSV   MOT1Y
>SSV   MOT1Z
>SSI   MOT1X
>SSI   MOT1Y
>SSI   MOT1Z
>END
BLANK CARD —last electric network branch
  MOTIX   MOT1A     -1.     10.
  MOTIY   MOT1B     -1.     10.
  MOTIZ   MOT1C     -1.     10.
BLANK CARD — ends switches
```

V. MOTOR STARTUP

For the motor startup, all state variables are initially set to zero. The induction motor torque vs. speed characteristic identical to those presented in [3] is shown in Figure 2. The motor startup can be delayed by a specific time to observe pre–event waveform.

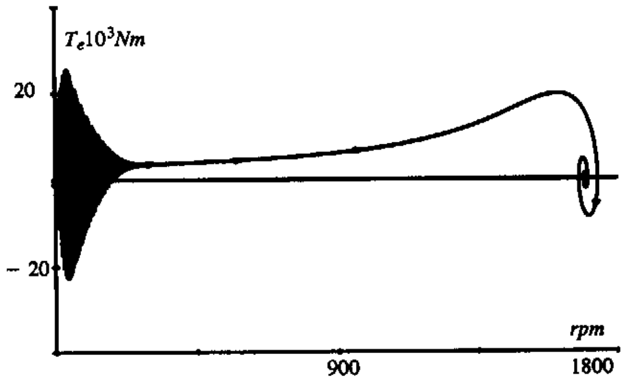

Figure 2. Induction Motor Torque vs. Speed

The induction motor A–phase current, startup torque and speed waveforms also identical to those presented in [3] are shown in Figure 3.

A. UM–Type 19 Induction Motor Comparison

For additional comparison, the 2300V, 2500hp induction motor was also modeled in ATP as a UM–type 19 machine.

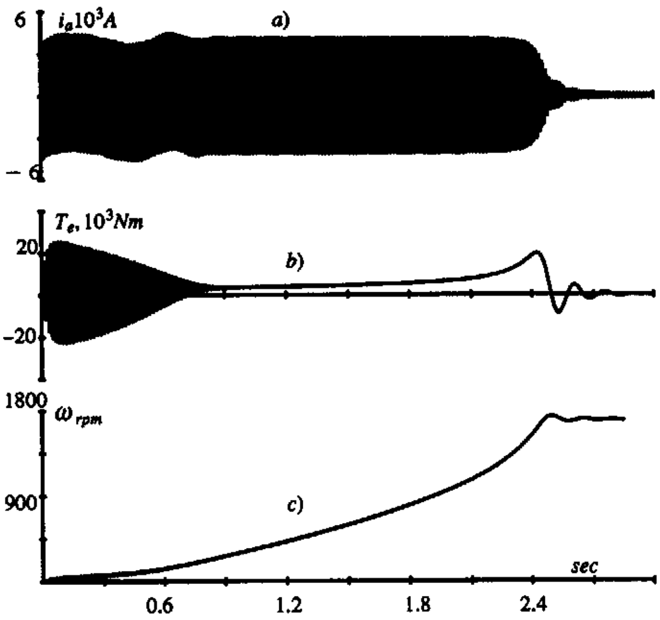

Figure 3. Induction Motor Startup vs. Time a) Current b) Startup Torque c) Speed

The torque curve of the machine represented in MODELS and the same machine represented as an UM–19 is shown in Figure 4.

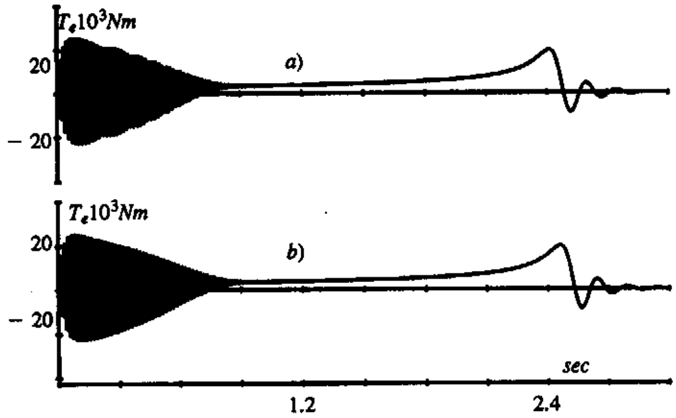

Figure 4. Induction Motor Torque vs. Time a) MODELS b) UM–19

The speed curve of the machine represented in MODELS and the same machine represented as an UM–19 is shown in Figure 5.

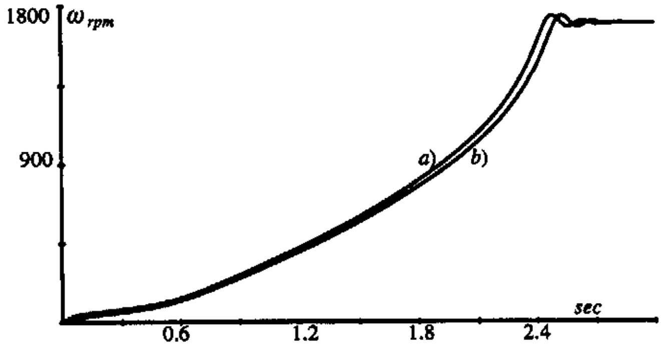

Figure 5. Induction Motor Speed vs. Time a) MODELS b) UM–19

Fig.4 and 5 shows that the two machine model startup response are nearly identical. The slight differences between the two models transient response illustrates the difference between one user defined model that is mathematically robust and the UM model less well defined.

VI. INITIALIZING A RUNNING MOTOR

To study the transient behavior of induction motors during a system disturbance, the motor model should be capable of self initialization. ATP does not allow simultaneous initialization of user defined models and the transmission network. Therefore, the user defined models and the network should be initialized separately.

A. *Transmission Network Initialization*

The transmission network for initialization is illustrated in Figure 6.

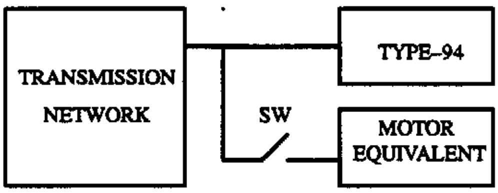

Figure 6. Network Initialization One Line Diagram

The type-94 branch has no impact on the ATP phasor solution performed a $t = 0$ and consequently does not effect the transmission network initialization. A steady state equivalent of the induction motor is needed at $t = 0$ to initiate the transmission network. The steady state motor equivalent is represented by the *R–L* circuits of each phase. A stand-alone MODELS routine is run first to determine the steady state motor equivalent *R–L* values, based on the motor parameters and initial motor speed. A time controlled switch *SW* shown in Fig.6 is inserted between the transmission network and the motor equivalent. *SW* is opened after one simulation time step, thus affecting only the transmission network solution.

B. *Induction Motor Initialization*

The induction motor initialization is performed based on the steady-state solution of the transmission network. In TABLE II. the type-94 branch *SSV* specify the busses where the steady-state voltages are measured and *SSI* specify switches where the steady state currents are measured. Based on the transmission network *SSV–SSI* input quantities the motor is initialized within the MODELS-INIT subroutine.

C. *Step Change In Mechanical Torque*

The induction motor response to a step change are shown in Figure 7.

The motor is assumed to be running at rated slip. The electrical torque is equal to the mechanical torque at 8.5kNm. At t = 0.4 sec the mechanical torque is changed to zero, and at t = 1.2 sec the mechanical torque is restored to its initial value.

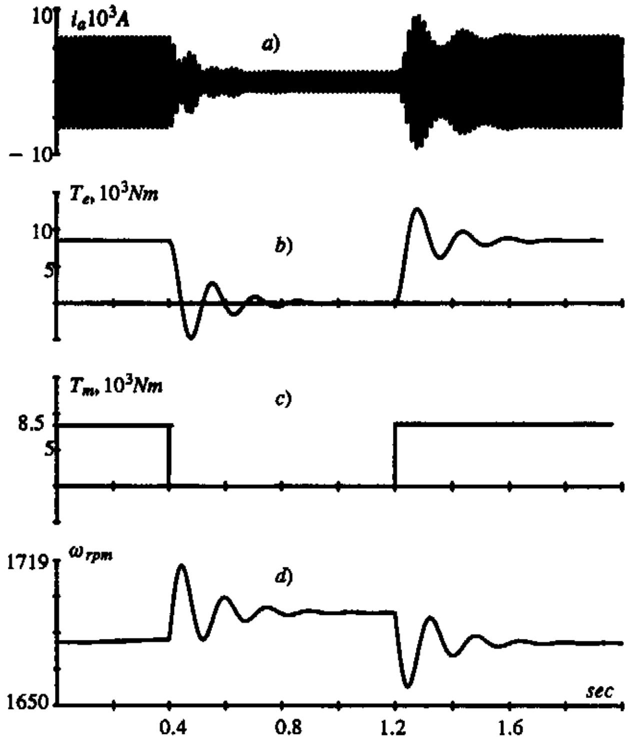

Figure 7. Induction Motor Response to Step Change vs. Time a) Current b) Torque Electrical c) Torque Mechanical d) Speed

VII. INDUCTION MOTORS OPERATING IN PARALLEL

Unlike the UM-19 machines, the iterated type-94 component in MODELS allows the parallel operation induction machines from a common bus shown in TABLE III.

TABLE III.

```
C — electric network branch
C —Motor 1 (2250Hp) Connection to the Network
94MOT1X  MOTOR ITER
94MOT1Y
94MOT1Z
 >DATA  XLS      0.226ohm  { stator leakage reactance, ohms
 >DATA  RS       0.029     { stator resistance, ohms
 >DATA  XR       0.226     { rotor leakage reactance, ohms
 >DATA  RR       0.022     { rotor resistance, ohms
 >DATA  XM       13.04     { magnetizing reactance, ohms
 >DATA  JJ       63.87     { inertia, kg-m2
 >DATA  PP       4.        { number of poles
 >SSV   MOT1X
 >SSV   MOT1Y
 >SSV   MOT1Z
 >SSI   MOT1X
 >SSI   MOT1Y
 >SSI   MOT1Z
C —
C —Motor 2 (500 Hp) Connection to the Network
94MOT2X  MOTOR ITER
94MOT2Y
94MOT2Z
 >DATA  XLS      1.206ohm  { stator leakage reactance, ohms
 >DATA  RS       0.262     { stator resistance, ohms
 >DATA  XR       1.206     { rotor leakage reactance, ohms
 >DATA  RR       0.187     { rotor resistance, ohms
 >DATA  XM       54.02     { magnetizing reactance, ohms
 >DATA  JJ       11.06     { inertia, kg-m2
 >DATA  PP       4.        { number of poles
 >SSV   MOT2X
```

```
>SSV    MOT2Y
>SSV    MOT2Z
>SSI    MOT2X
>SSI    MOT2Y
>SSI    MOT2Z
>END
BLANK CARD —last electric network branch
  MOTIX    MOT1A     -1.     10.
  MOTIY    MOT1B     -1.     10.
  MOTIZ    MOT1C     -1.     10.
C
  MOT2X    MOT1A     -1.     10.
  MOT2Y    MOT1B     -1.     10.
  MOT2Z    MOT1B     -1.     10.
BLANK CARD — ends switches
```

Multiple instances of the same induction MOTOR model can be used in the same application. The Hp ratings of the machines in parallel may the same or it may be different as shown in TABLE III. and illustrated in Figure 8.

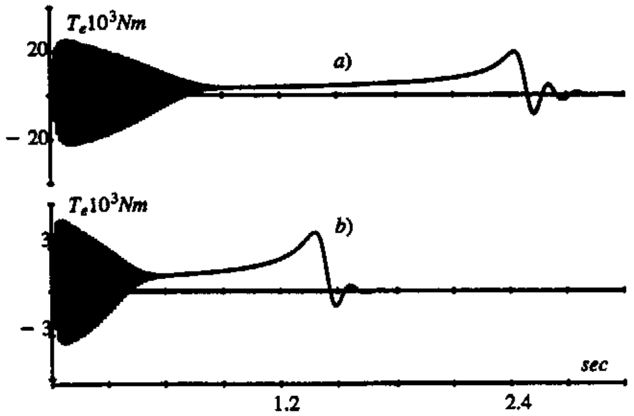

Figure 8. Induction Motor Torque vs. Time a) 2250Hp b) 500Hp

VIII. CONCLUSION

The authors presented an application of a new development in MODELS solver and its interface with ATP that allow the simultaneous solutions of any sets of user defined linear and nonlinear differential algebraic equations, all within same network solution time step. The application of this new development is demonstrated with a 2300kV, 2500hp induction motor computer model.

A new type-94 interface is introduced between the induction motor in MODELS and the ATP transmission network. The induction motor response to a step change shows that the user defined induction machine model within MODELS responds accurately. The new development allows the simulation of several motors in parallel.

The authors expect that the linear flux linkage equations can be expanded to represent internal motor faults. The results, will be presented in a future paper.

IX. GLOSSARY

ψ_{ds} – PSIDS – Stator, direct axis. Flux linkage / second.

ψ_{qs} – PSIQS – Stator, quadrature axis. Flux linkage / second.

ψ_{0s} – PSI0S – Stator, Zero Sequence, Flux / second

ψ_{dr} – PSIDR – Rotor, direct axis. Flux linkage / second.

ψ_{qr} – PSIQR – Rotor, quad. axis. Flux linkage / second.

ψ_{0r} – PSI0R – Rotor, Zero Sequence, Flux / second

Hp – Horse power

p – derivative operator

ω_r – WR – rotor angular speed

ω_s – WS – rotor synchronous speed

PSIDSPR– Stator, direct axis. Flux Derivative

PSIDRPR– Rotor, direct axis. Flux Derivative

PSIQSPR– Stator, quad axis. Flux Derivative

PSIQRPR– Rotor, quad axis. Flux Derivative

PSI0SPR– Stator, zero axis. Flux Derivative

PSI0RPR– Rotor, zero axis. Flux Derivative

i_{ds} – CDS – Current Stator, direct axis

i_{qs} – CQS – Current Stator, quad. axis

i_{dr} – CDR – Current Rotor, direct axis

i_{qr} – CQR – Current Rotor, quad. axis

X. REFERENCES

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XI. BIOGRAPHIES

Jules Esztergalyos PE. was born in Baja, Hungary in 1940. He received his BSEE from Washington State University, Pullman, WA. in 1965. He was employed by BPA T&E section in 1965, and worked for BPA control and protection section since 1968. Mr. Esztergalyos became BPA's Principal System Protection Engineer in 1985. He received numerous awards for designing generator dropping, dynamic braking, high-speed grounding and single pole trip schemes. (E-mail: jesztergalyos@bpa.gov)

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Laurent Dube was born in Montreal, Canada in 1949. He received his B.A. ('67) and EE ('72) degrees at the Univ. of Sherbrooke, Quebec, and a Masters in control systems ('73) at Ecole Polytechnique in Montreal. He developed the TACS ('75) and MODELS ('88) facilities of EMTP and ATP. His main technical interest is the description and the simulation of dynamic systems. He is member of IEEE Power Engineering Society, the IEEE Computer Society for Computer Simulation and the Association for Computing. (E-mail: dube@peak.org)