Electromagnetic Transient Simulation of Induction Machine based on QSS Algorithm

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***Abstract*—This paper explores the feasibility of transient simulations power system based on discrete event system (DEVS), where the Quantized State System (QSS) algorithm is used for numerical integrations. An induction machine model based on DEVS formalism is built up. Moreover, to guarantee the efficiency and accuracy of transient simulations based on QSS, an algorithm for optimal selection of quantum is derived. Test results with comparisons with traditional EMTP simulations are presented, which also validate the proposed simulation method.**

***Index Terms*-- DEVS; Electromagnetic transients; Power system modeling; Quantized state system; Simulation**

I. Introduction

A. Motivation

Discrete Event System (DEVS) has been applied maturely in the cyber system simulation [2]. Thanks to developments of Quantized State System (QSS) algorithm, DEVS becomes applicable for continuous time system simulations, which is a promising solution for dynamic analysis of cyber and physical systems.

For integrated simulations of cyber physical power systems, the feasibility of transient simulations using DEVS formalism and QSS algorithm is worth to being explored. In this work, an induction machine is modeled by DEVS, which includes basic mechanic and electrical relationships in the power systems. Then, the optimal quantum is selected to enhance the accuracy and efficiency of simulations with the proposed model.

B. Literature Review

Many testbeds are developed to simulate cyber physical system (CPS). Hahn presents an overview of main work in this area [1]. Most testbeds use different structures in simulating cyber side and physical side respectively, with a proper interface between them. Differently, the unified modeling of cyber and physical components can be achieved in DEVS formalism. DEVS is first proposed by Zeigler in [2]. It has been widely used in network simulation. In 2001, Kofman [3] developed a method based on DEVS formalism to solve DAEs, which is named QSS. Later, high order interpolation methods are adopted to improve the performances of QSS [4], [5]. Then, QSS exhibits nice stability and error bound properties, which is discussed in [6], [7]. To avoid the numerical shock [7] in QSS, James proposes an Adams-Bashforth type scheme, which takes the minimum time step into consideration. Kofman also developed a proper technology named LIQSS in [9], [10]. In LIQSS, a derivative forecasting method is applied. In practice, LIQSS is better than Adams-Bashforth type scheme.

QSS also has an asynchronous property which gives it great advantages in parallel and distributed computing. Reference [11] developed a method allowing for the translation of a restricted class of Modelica models to parallel simulation code, targeted for the Nvidia Tesla architecture. Reference [12] proposed an extension to the DEVS formalism called VECDEVS which allowed to represent large scale systems in a graphic block diagram way and simulate it in parallel computing. Bergero and Kofman also developed a software named PowerDEVS [13] based on VECDEVS. Reference [14] presented a tool called M/CD++ to build DEVS models using Modelica [15]. Brooks added QSS algorithm into CyPhySim [16], a simulation software based on Ptolemy Ⅱ. References [17], [18] discussed the feasibility of QSS in distributed computing.

Actually, different researchers have tried to apply QSS in the simulation of power systems. Laurent Capocchi [19] and Lan Tong [20] tested PowerDEVS with a stator model of AC machine and a SIMB model respectively. However, none of them has modeled the mechanic and electrical parts of an induction machine together in DEVS. Kofman also studied the application of QSS in power system [21]. He built up a switch model of power source. Besides, [10], [13] also included some test cases of electrical circuit. However, these works are still limited to the specific electrical circuit like buck circuit or switch model.

C. Contribution

In this paper, electromagnetic transient simulations of an induction machine based on DEVS formalism and QSS algorithm are implemented and tested. Two contributions are included in this paper.

- Building an induction machine model based on DEVS and providing a method to choose the optimal quantum.
- Testing the efficiency and accuracy of QSS method by an induction machine model.

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D. Paper Organization

The paper is organized as follows. Section 2 introduces DEVS formalism and QSS algorithm briefly. Section 3 shows the EMTP modeling of the induction machine, presents the induction machine model in DEVS and proposes the optimal quantum option method. Test results are presented in Section 4. Then, Section 5 concludes this article.

II. DEVS MODELING AND QSS ALGORITHM

A. DEVS and QSS

The basic idea of DEVS is converting continuous time physical processes to discrete events occurring chronologically. As shown in Figure.1, t_i $(i = 0,1,2,3)$ represents the time when event occurs and M_i $(i = 0,1,2,3)$ stands for system state. t_{ai} $(i = 0,1,2,3)$ means the duration of a certain state. System state M_i changes when an event occurs and stays for t_{ai}. In this way, a continuous physical process is interpreted as a sequence of states changes.

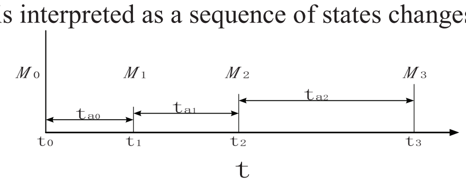

Figure.1. The organization of DEVS

QSS is an integrated algorithm based on DEVS. Given differential equations

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}, t, \boldsymbol{u}) \tag{1}$$

QSS approximates it by

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{q}, t, \boldsymbol{u}) \tag{2}$$

where $\boldsymbol{q}$ is the quantized state vector,

$$q_i(t) = \begin{cases} x_i(t) & |q(t) - x(t)| > Q_i \\ q_i(t^-) & \text{otherwise} \end{cases} \tag{3}$$

Q_i is called quantum.

Whenever a state variable increases or decreases by Q, an event of state change occurs. The occurrences of events chronologically drive the simulation to go ahead. Thus, continuous-time (CT) models are transferred to the discrete-state models used by DEVS.

Generally, from given $t = t_1$ and $\boldsymbol{q}(t_1)$, integrations of (1) based QSS method require following procedures.

1. Obtain the derivatives of each state according to (2).
2. Obtain the minimum time interval of each state variables changing by Q as
$$\Delta t = \min\,(Q_i/x_i) \tag{4}$$
3. Update the state variables as
$$\boldsymbol{x}(t_1 + \Delta t) = \boldsymbol{x}(t_1) + \dot{\boldsymbol{x}}(t_1)\Delta t \tag{5}$$
4. Update $\boldsymbol{q}$ as (3) to get $\boldsymbol{q}(t + \Delta t)$.

Details of QSS method can be found in [2] and [3]. It should be noted that the accumulated errors of integrations based on QSS are limited in an "error bounds" [6], [7], as shown in (6).

$$|\widetilde{\boldsymbol{x}}(t) - \boldsymbol{x}_a(t)| \leq \boldsymbol{RQ} \tag{6}$$

where $\widetilde{\boldsymbol{x}}(t)$ is the result obtained by QSS algorithm. $\boldsymbol{x}_a(t)$ represents the actual values. $|\widetilde{\boldsymbol{x}}(t) - \boldsymbol{x}_a(t)|$ stands for integration errors and $\boldsymbol{R}$ is determined by the coefficients matrix of differential equations. $\boldsymbol{RQ}$ is "error bounds".

B. Challeges of applying DEVS in power system simulations

The selection of Q for each state variable is a critical issue when applying the QSS algorithm in power system simulations. According to (4), a too small quantum Q leads to small time interval and large amount of events. According to (6), a too large quantum Q could cause unacceptable errors. Therefore, to guarantee the accuracy and efficiency of simulations using QSS, value bounds of Q should be analyzed carefully. In Section Ⅲ, principles of determining value of Q are addressed. The up and low bounds of Q are also derived.

III. INDUCTION MACHINE MODEL AND QUANTUM SELLECTION

A. EMT modeling of induction Machine

Induction machines are basic components in power systems. Three different models of induction machines are widely used in electromagnetic transient simulations. The dq model [22] is based on rotating reference frame [21], which needs dq transformation as an interface. The Phase domain model [23] is based on phase domain frame, which avoids dq transformations with costs as time-varying coefficients. The VBR model [24] puts stator in the phase domain frame while rotor in the rotating reference frame. Thus it also requires dq transformation for interfacing with power networks.

In this paper, the dq model is adopted. The state equation of induction Machine can be written as

$$u_{dq} = p\lambda_{dq} + A(\omega)\lambda_{dq} + R_{dq}i_{dq} \tag{7}$$

$$\lambda_{dq} = Xi_{dq} \tag{8}$$

where, u_{dq}, λ_{dq} and i_{dq} represent the voltage, flux and current of d- and q-axis respectively. ω is rotor speed.

$$u_{dq} = (u_{ds}, u_{qs}, u_{dr}, u_{qr})$$
$$\lambda_{dq} = (\lambda_{ds}, \lambda_{qs}, \lambda_{dr}, \lambda_{qr})$$
$$i_{dq} = (i_{ds}, i_{qs}, i_{dr}, i_{qr})$$

X and R_{dq} can be obtain from the parameters of the induction machine. p means derivation.

$$A = \begin{bmatrix} 0 & -1 & & \\ 1 & 0 & & \\ & & 0 & -1+\omega \\ & & 1-\omega & 0 \end{bmatrix}$$

Substituting (8) into (7),

$$u_{dq} = Xpi_{dq} + R_e i_{dq} \tag{9}$$
$$R_e = A(\omega)X + R_{dq}$$

The EMTP method is widely used for electromagnetic transient simulations, in which time is discretized to numeric integrate (9) as follows.

$$i_{dq}(t) = Yu_{dq}(t) + i_{h\_dq}(t) \tag{10}$$

$$i_{h\_dq}(t) = G_1 i_{dq}(t) + G_2 i_{dq}(t - \Delta t) + G_3 u_{dq}(t - \Delta t) \tag{11}$$

In (11), G_1, G_2 and G_3 are constant which is derived from machine parameters. The expression of i_{h_dq} includes a term of $i_{dq}(t)$, which needs to be predicted in each iteration. Also, a proper interface is needed to transform variables in dq references to phase domain ones. Details of EMTP simulations using the dq model can be referred to [28]. As illustrated in Figure.2, at time t, the solution of power network equations gives a boundary voltages in phase domain for an induction machine. Then, the value of state variables of the induction machine at time t can be calculated. After that, according to (10), the current i_{dq} at time $t+\Delta t$ can be obtained.

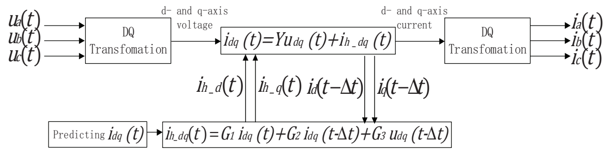

Figure.2. The caculation progress of dq model based on EMTP

B. DEVS model of Induction Machine

To apply DEVS formalism to the induction machine model, substitute (8) into (7) and rewrite it as

$$\mathbf{p}\boldsymbol{\lambda}_{dq} = -\left(\mathrm{A}(\boldsymbol{\omega}) + \boldsymbol{R}_{dq}\boldsymbol{X}^{-1}\right)\boldsymbol{q}_{dq} + \mathbf{u}_{dq} \quad (12)$$

where $\boldsymbol{q}_{dq} = (q_{ds}, q_{qs}, q_{dr}, q_{qr})$ and $\boldsymbol{q}_{dq}$ is a quantized state vector as (3).

The mechanical equations can be also quantized as

$$\mathbf{p}\omega = \left(T_l - T_e(\boldsymbol{q}_{dq})\right)/(2H) \quad (13)$$

$$\mathbf{p}\theta = 1 \quad (14)$$

An interface of dq transformation is also needed in DEVS formalism. The phase domain current can be obtained by (15),

$$\boldsymbol{i}_{abc} = \boldsymbol{P}\boldsymbol{D}\boldsymbol{\lambda}_{dq} \quad (15)$$

where $\boldsymbol{P}$ is dq transformation and $\boldsymbol{D}$ can be calculated from machine parameters.

The model of induction machine based on DEVS formalism can be illustrated in Figure.3. The essential difference between Figure.2 and Figure.3 is how to determine Δt. In EMTP Δt is a constant defined before simulations, while in QSS, it is a variable determined by (4).

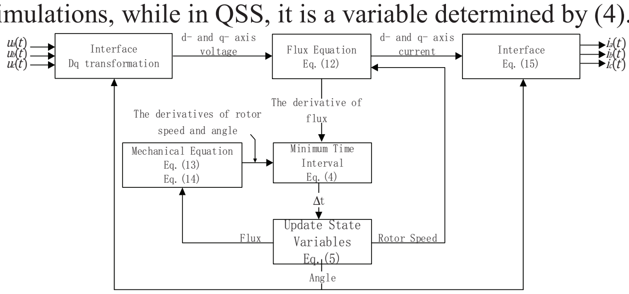

Figure.3. Induction Machine Model Based on DEVS

C. Optimal Quantum Selction method

A large number of state variables will be involved in transient simulations of a complicate system. Optimal quantum Q is needed for them, with following two principles.

1) Selecting a small enough Q to ensure the accuracy of the simulation.

Equation (6) shows the error of solving differential equations using QSS algorithm. Apply $\|\cdot\|$ to the both side of (6), where $\|\cdot\|$ represents ∞-norm. Then, it can be seen that if the maximum acceptable error is $\boldsymbol{e}_{max}$, the quantum Q must satisfy

$$\|\boldsymbol{Q}\| \leq \|\boldsymbol{R}\|^{-1}\boldsymbol{e}_{max} \quad (16)$$

In the power system simulation, the differential equations as well as algebraic equations are required to be solved. When an event happened, $\boldsymbol{q}$ is updated. Then $\boldsymbol{q}$ is transferred to the algebraic equations as input variables. The results of algebraic equations becomes the input variables of differential equations. If the model of a system includes nonlinear algebraic equation, Newton-Raphson algorithm is needed to solve it.

According to [6], the error of QSS algorithm can be written as

$$\|\boldsymbol{e}(\mathrm{t})\| \leq \|\boldsymbol{R}e\| \quad (17)$$

where $\boldsymbol{e}(\mathrm{t})$ is the error of QSS algorithm, e is the error of algebraic equations here.

According to [26], e can be estimated as

$$e < \frac{1}{1+\sqrt{1-\alpha}}\frac{2(\|\boldsymbol{HQ}\|+\|\boldsymbol{H}\|k_0)}{\Phi - Mk_0 - 2\|\boldsymbol{HQ}\|} \quad (18)$$

where $\boldsymbol{H}$, Φ, M and α can be calculated according to the algebraic equations. $k_0 = \|x_1 - x_0\|$. Details about coefficients of (18) can be found in [26]

In QSS, k_0 can be written as $k_0 = p\|\boldsymbol{Q}\| (p \geq 1)$. Subsisting (18) into (17) and enlarge the right side of (17), (19) is obtained.

$$\|\widetilde{\boldsymbol{x}}(t) - \boldsymbol{x}_a(t)\| \leq \frac{2(1+p)\|\boldsymbol{H}\|\|\boldsymbol{R}\|}{(1+\sqrt{1-\alpha})\Phi}\|\boldsymbol{Q}\| \quad (19)$$

where p is a constant smaller than 1.

From (19), the upper bound of Q can be obtained as

$$\|\boldsymbol{Q}\| \leq \frac{(1+\sqrt{1-\alpha})\Phi\boldsymbol{e}_{max}}{2(1+p)\|\boldsymbol{H}\|\|\boldsymbol{R}\|} \quad (20)$$

2) Selecting a big enough Q to reduce the number of events as well as improve the efficiency of the simulations.

As shown in the procedures of QSS algorithm, the occurrence of an event means an iteration. Thus the efficiency of QSS algorithm can be measured by the amount of events. Figure.4 shows an example of a state variable changes as time goes on. According to QSS, the event amount in the change process of this state variable can be written as

$$N_{ep} = (|x_2 - x_1| + |x_3 - x_2| + |x_3 - x_4| + |x_5 - x_4|)/Q \leq 4 \times |x_{max} - x_{min}|/\mathrm{Q} \quad (21)$$

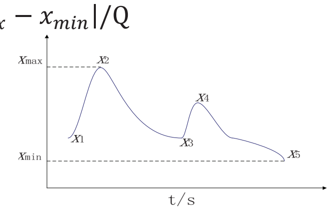

Figure.4. An example of state variable

Hence the total event number of a system can be estimated using (22).

$$N_{eQSS} = \sum_{i=1}^{n_s} N_{epQSS_i} = \sum_{i=1}^{n_s}\left(k_i|x_{max_i} - x_{min_i}|/Q_i\right) \quad (22)$$

where N_{eQSS} is the amount of events and N_{epQSS_i} is number of events belonging to ith state variable. k_i is a constant parameter can be estimated according to the frequency and magnitude of dynamic related to corresponding state variables. n_s is the number of state variables.

Similarly, in EMTP the number of "events" can be written as

$$N_{eEMTP} = \frac{T}{\Delta t} \quad (23)$$

where T is the simulation length and Δt is the integration step. If we set $N_{eQSS} \leq N_{eEMTP}$, a sufficient condition can be obtained as (24)

$$Q_i \geq \frac{k_i|x_{max_i}-x_{min_i}|n_s\Delta t}{T} \quad (24)$$

where subscript i means the ith state variable. $|\boldsymbol{x_{max_i}} - \boldsymbol{x_{min_i}}|$ represents the range of each state variables.

IV. TEST CASE

An induction machine connected to an infinite bus is taken as the benchmark in following tests. The parameters related are shown in TABLE I.

TABLE I. PARAMETERS

Rated Voltage(L-L)	0.38KV
Rated Power	0.1MVA
Rated Frequency	50Hz
J	1.8s
Stator Resistance	0.043pu
Rotor Resistance	0.001pu
Stator Inductance	0.0613pu
Rotor Inductance	0.0613pu
Magnetizing Inductance	1pu

According to TABLE I. , we can obtain

$$\boldsymbol{R_{dq}X^{-1}} = \begin{bmatrix} 0.3612 & & -0.3403 & \\ & 0.3612 & & -0.3403 \\ -0.0079 & & 0.0084 & \\ & -0.0079 & & 0.0084 \end{bmatrix}$$

A. Optimal Quantum selection

The model of the induction machine has 6 state variables, which requires 6 quantum determined before the simulation.

As $\boldsymbol{e_{max}} = 0.1$ is adopted, the upper bound of Q can be obtained for flux differential equations and mechanical differential equations separately by applying (20).

For flux equations,

$$\|\boldsymbol{Q}\| \leq 4 \times 10^{-4} \quad (25)$$

For ω_r of mechanical equations,

$$\|\boldsymbol{Q}\| \leq 2.6 \times 10^{-5} \quad (26)$$

For θ_s, since its derivative is a constant, the upper bound of Q is $\boldsymbol{e_{max}}$.

Applying (24), the lower bound of each Q can be obtained. Being conservative, k is chosen as small as possible so that the lower bounds of Q is small enough. TABLE II. shows the results about the lower bounds of Q.

TABLE II. LOWER BOUND OF Q

State Variable	$\lvert x_{max_i} - x_{min_i}\rvert$	k	Lower Bound of Q
$\boldsymbol{\psi_{ds}}$	1.6	5.5	1.05×10^{-5}
$\boldsymbol{\psi_{qs}}$	0.6	5.5	3.96×10^{-6}
$\boldsymbol{\psi_{dr}}$	1.4	5.5	9.24×10^{-6}
$\boldsymbol{\psi_{qr}}$	0.6	20	1.44×10^{-5}
$\boldsymbol{\omega_r}$	1	1.5	1.80×10^{-6}
$\boldsymbol{\theta_s}$	**500π**	1	1.884×10^{-4}

It should be noted that (20), (24) and TABLE II. only provide suggestions about the selection of Q. If the expected error $\boldsymbol{e_{max}}$ is chosen improperly, then no feasible quantum can be used due to the lower bound is bigger than upper bound.

B. Test results

In this case, for simplicity, Q is chosen as (27).

$$\begin{bmatrix} Q_{ds} \\ Q_{qs} \\ Q_{dr} \\ Q_{qr} \\ Q_{\omega_r} \\ Q_{\theta_s} \end{bmatrix} = \begin{bmatrix} 0.0001 \\ 0.0001 \\ 0.0001 \\ 0.0001 \\ 0.00001 \\ 0.01 \end{bmatrix} \quad (27)$$

The actual value is obtained from PSCAD with an integration step 1us. The simulation length is 5s, thus the number of "event" in EMTP is 5×10^{6}. TABLE III. and 0show the number of events and the error of simulations using QSS algorithm respectively.

TABLE III. NUMBER OF EVENTS

State Variables	N_{epQSS}	Actual number of events
$\boldsymbol{\psi_{ds}}$	88000	101661
$\boldsymbol{\psi_{qs}}$	33000	63922
$\boldsymbol{\psi_{dr}}$	77000	54049
$\boldsymbol{\psi_{qr}}$	120000	111504
$\boldsymbol{\omega_r}$	150000	184299
$\boldsymbol{\theta_s}$	157079	157079
Total	625079	672514

It can be seen in TABLE III. that though the event number of flux is not so exactly, the number of total events is accurately estimated by (27). In the 0 the error is defined as absolute error as (28). Error estimations from (20) are much bigger than actual errors, which is caused by the conservative derivation of (6). Similar phenomenon has also been reported in [7].

$$\boldsymbol{Error} = \|\tilde{\boldsymbol{x}}(t) - \boldsymbol{x}_a(t)\| \quad (28)$$

TABLE IV. ERROR

State Variables	Estimated Error	Actual Error (Steady)
$\boldsymbol{\omega_r}$	0.1	0.0002
$\boldsymbol{T_e}$	0.1	0.02
$\boldsymbol{i_{as}}$	0.1	0.05

For comparisons, simulation results obtained with quantum defined in (29) are also tested. In (29), Q_{ds} increases tenfold while Q_{dr} decreases tenfold compared to (27). Substituting (29) into (16), we can have $\boldsymbol{e_{max}} = 0.243$. Substituting (29) into (24), N_{eQSS} can be estimated as 1088879. Thus, according to the proposed performance model, simulations with (27) should be more accurate and efficient than those with (29).

$$\begin{bmatrix} Q_{ds} \\ Q_{qs} \\ Q_{dr} \\ Q_{qr} \\ Q_{\omega_r} \\ Q_{\theta_s} \end{bmatrix} = \begin{bmatrix} 0.001 \\ 0.0001 \\ 0.00001 \\ 0.0001 \\ 0.00001 \\ 0.01 \end{bmatrix} \quad (29)$$

TABLE V. NUMBER OF EVENTS WITH (27) AND (29)

State Variables	Eq.(27)	Eq.(29)
$\boldsymbol{\psi_{ds}}$	101661	33749
$\boldsymbol{\psi_{qs}}$	63922	66598
$\boldsymbol{\psi_{dr}}$	54049	564270
$\boldsymbol{\psi_{qr}}$	111504	113557
$\boldsymbol{\omega_r}$	184299	183953
$\boldsymbol{\theta_s}$	157079	157079
Total	672514	1119206

TABLE V. shows the comparison of actual events number of simulations with different Q configurations. Consistent with theoretical analysis, the number of events occurred in simulation with (27) is less than that of simulation with (29).

Fig.5-7 show the startup process of the induction machine studied with constant torque. 0 shows the current of stator. The current waves obtained from simulations with (27) and (29) share the same shape. From Figure.2 and Fig. 7, it can be observed that simulation results with (27) is more accurate than that using (29).

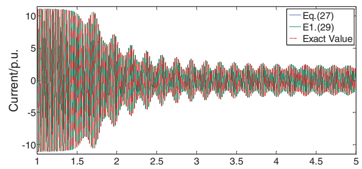

Figure.1. Current of Stator

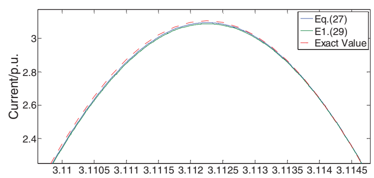

Figure.2. An enlarged view of current

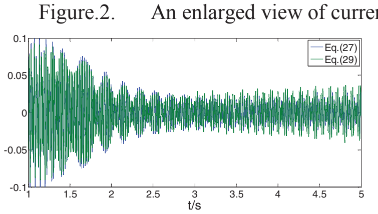

Figure.3. Error of current

It can be seen that the proposed quantum selection method is effective for QSS based simulations.

V. Conclusions

An induction machine model based on DEVS formalism is built to test the feasibility of QSS algorithm. Also, a method of selecting optimal quantum Q is discussed in this paper. Test results validate the proposed model and algorithm, as well as the optimal quantum selection method.

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