ORIGINAL RESEARCH PAPER

Performance analysis of a novel outer rotor flux-switching permanent magnet machine as motor/generator for vehicular and aircraft applications

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Abstract
Herein, a novel study on outer rotor flux-switching permanent magnet (OR-FSPM) machines for motor/generator applications is presented. An improved magnetic equivalent circuit (MEC) is used for saturable machine model, and the performance analysis is presented in both dynamic and steady-state cases. A flexible MEC-based method is used, where the machines with arbitrary properties can be analysed. Moreover, the model accuracy can be tuned by selective parameters in the proposed method. It is shown that the machine can be used as a high efficiency 400 Hz Ground Power Unit (GPU) for aircraft application. Furthermore, the machine usage for in-wheel application in the hybrid and electric vehicles (HVs and EVs) is analysed. Comparison with 2D and 3D finite-element-method (FEM) shows the effectiveness and accuracy of the proposed MEC method, where shorter processing time is obtained compared with FEM.

1 | INTRODUCTION

The outer rotor permanent magnet synchronous machine (OR-PMSM) is a special electrical machine (EM) which has been investigated in industry thanks to its structural compatibilities and high-torque density. Moreover, the outer rotor permanent magnet synchronous machines (OR-PMSMs) can be used as a direct-drive machine which can be directly connected to the traction subsystems [1]. Modelling, control and design of OR-PMSMs have been investigated many times for performance and capability analysis. For modelling, an analytical-based method is presented in Ref. [2], where lumped magnetic circuit and 2D Poisson’s/Laplace’s equations are used. Electromagnetic equations and finite-element-method are used in Refs. [3,4], but the dynamic performance is not considered. The OR-PMSM design and performance analysis are investigated in Refs. [5,6]. In Ref. [5], four OR-PMSMs with different pole-slot combinations are designed by basic equations, and in Ref. [6], special OR-PMSM with amorphous stator core is designed, where a FEM-based simulation is used for validation. A comparative study for two OR-PMSMs with different rotor structures is performed in Ref. [7] for the machines performances analysis. Influence of ratio of the external diameter to the machine stack length on the OR-PMSMs performance is studied in Ref. [8]. Pole-slot combination and magnet arrangement influence on the outer and inner rotors PMSMs are addressed in Ref. [9], and the steady-state characteristics are studied. In-wheel application is another important usage in EVs and HVs which is investigated many times by researchers, thanks to the direct-drive capability of OR-PMSMs. An outer rotor flux switch wound field machine for in-wheel application is analysed by FEM in Ref. [10], but analytical method is lacked. The V-shape and I-shape magnets for two outer rotor flux-switching permanent magnets machine is analysed in Ref. [11], and the machines characteristics are studied for in-wheel application. A non-segmental outer rotor switch reluctance machine is analysed in Ref. [12] for in-wheel usage by FEM, where the torque and current characteristics are studied. Another important equipment in the vehicular systems is ground power units (GPUs) which is a 110–120 V, 400 Hz generator for grounded aircrafts [13]. The flux-switches machines (FSMs) are recently proposed for some applications such as electric aircrafts [14,15], linear machines [16], and vehicular systems [17], thanks to its high torque density. These machines are recently investigated in many applications such as GPUs. As a new work, a three-phase FSM
with inner and outer rotors is presented in Ref. [18] as a GPU, and analysis is performed by FEM, but the obtained voltage regulation is not suitable. A novel structure for OR-FSM is presented in Ref. [19], where the Back-EMF analysis is performed by FEM, but the dynamic response and analytical method are lacked. The FEM-based method is the most investigated approach for modelling and analysis of electric machines which has been used many times by researchers. Although, the FEM is a powerful tool for the mentioned aim, it has some drawbacks such as intensive processing and large simulation time. Moreover, individual FEM-based programming is needed for each case study, which can cause some difficulties in the modelling and analysis. Magnetic Equivalent Circuit (MEC), is another powerful method for modelling and analysis of electric machines, where all of the harmonics effects can be modelled. The method was initially proposed by Ref. [20], but this has been used in many new researches thanks to its capability. As a recent work, a partitioned stator FSM is modelled in Ref. [21], where an improved MEC is proposed for the machine. Another new work is presented in Ref. [22] for OR-PMSM, where a flexible MEC is addressed. The presented MEC can be simply modified for many types of electric machines such as FSMs, and etc. This method is also used for Ladder-Secondary linear induction machine in Ref. [23]. This method is now used for this research for modelling and analysis of an OR-FSPM machine, where the machine capability for in-wheel application and ground power unit (GPU) is studied. The novelties herein can be summarized as follows:

- Modelling of OR-FSPM by a flexible MEC method, based on the presented technique in Ref. [22].
- Dynamic simulation of OR-FSPM for in-wheel application.
- Analysis of OR-FSPM as a GPU for aircraft application.

2 | PROPOSED OR-FSPM MACHINE

Structure of the studied OR-FSPM machine is shown in Figure 1, where a 28-pole/36-slot OR-FSPM is considered as a sample case in the figure. Considering \( n_{pm} \) PMs, \( 2n_{pm} \) poles are produced in the rotor.

Each PM is magnetized tangentially and is sandwiched by two magnetic materials, where a non-magnetic material is used as a pole insulator.

The machine principle can be found in Ref. [19], where the flux switching in the stator teeth is clarified.

3 | MODELLING APPROACH OF OR-FSPMS MACHINE

The proposed MEC in Ref. [22] is considered herein. The used MEC for OR-FSPM machines is shown in Figure 2, where all the model details are clarified in the figure. It is notable that the presented MEC in Ref. [22] was proposed by authors for OR-PMSMs with radially magnetized PMs, and the MEC-based equations are clarified in Ref. [21]. Some minor modifications are necessary because of tangentially magnetized PMs, instead to radially type. The air-gap permeances are shown in Figure 3, where the air-gap fluxes are modelled by linear conductances \( G_{ij} \) for \( 1 \leq i \leq nr \), and \( 1 \leq j \leq ns \) [20–22]. The used MEC accuracy can be tuned by tuneable defined parameters in Table 1. In addition, the machine properties and tuneable parameters are listed in the table. Noticing to Figure 1, the number of obtained flux tubes in the defined MEC can be written as Table 2. Moreover, the flux tubes geometries are shown in Figure 4, and the relative reluctance should be computed by Equation (1). The \( \mu_{s}(\theta) \) is a function for core nonlinearity model, where \( \mu_{s}(\theta) \approx 1 \) should be considered for the air and PM flux tubes. A new flexible function for relative permeability is considered, where the core non-linearity curve fitting can be performed by selective parameters (a, b, and c). These parameters can be tuned experimentally for the best fitting of the magnetization curve on the actual material curve.

\[
R_{ij} = \begin{cases} 
\int_{r_{i}}^{r_{j}} \frac{dr}{\mu_{0} \mu_{r}(B_{ij}) r a_{ij} l} = \ln \left( \frac{r_{j}}{r_{i}} \right) & \text{for radially flux tubes} \\
\int_{r_{i}}^{r_{j}} \frac{r a_{ij} l dr}{\mu_{0} \mu_{r}(B_{ij}) r} = a_{ij} \ln \left( \frac{r_{j}}{r_{i}} \right) & \text{for tangentially flux tubes}
\end{cases}
\]  

(1a)
\[
\text{Bi} = \frac{q_{ij} A_i}{A_j} \text{ where } A_i
\]

\[
= \begin{cases} 
\frac{r_{ij} + r_{ij}'}{2} a_{ij} & \text{for radially flux tubes} \\
I_i (r_{ij} - r_{ij}) & \text{for tangentially flux tubes}
\end{cases}
\]

The proposed function is written in Equation (2) as well as some various curves are shown in Figure 5. In the considered MEC, there are two MMF sources for the flux production, as shown in Figure 2. One for the rotor magnets \((F_i, i = 1, 2, 3),\)
and the other for stator windings (\(F_s\)). The mentioned sources are written in Equation (3), where the \(l_{pm}\) is the length of the PMs flux tubes in the \(i\)th zone. Moreover, \(W_i\) is the turn map matrix of the stator windings.

\[
\mu_r(B) = a \cdot \left( e^{-\left(\frac{B}{B_0}\right)^2} + e^{-\left(\frac{B}{B_1}\right)^2} \right) \tag{2} 
\]

\[
\begin{align*}
F_i &= \frac{B_i l_{pm}}{\mu_0 H_{pm}} & \text{for PMs | PMs flux tubes} \\
F_i &= \frac{1}{2} \frac{B_i l_{pm}}{\mu_0 + \mu_{pm}} & \text{for PMs | Magnetic materials flux tubes} \\
F_s &= F_{s1} \ldots F_{sn} &= W \cdot [i_A \ i_B \ i_C]^T 
\end{align*} \tag{3} 
\]

4 | SOLVING PROCEDURE

Dynamic model of the OR-FSPM machine can be obtained by solving the presented MEC equations. The minimum number of equations in both magnetic and electric types should be obtained. In the next part, the general form of the mentioned equations are defined in matrix form.

4.1 | Magnetic equations

Based on the Kirchhoff's current and voltage laws (KVL and KCL), the general form of the magnetic equations can be written as Equations (4)–(13), where the details of the equations can be

4.2 | Electric and mechanical equations

Electric and mechanical equations are in linear differential type. In these equations, the winding configuration (\(Y, Y_n\), or \(\Delta\)
connections) is modelled by $L$ matrix defined in Equation (14). Moreover, the equations should be converted to algebraic time-stepping form. The converted equations are written in

\[ Mc.Ar1.\varphi 10(t) + 0.5.Mc.Ar1.\varphi 9(t) + \left( L + \frac{\Delta t}{2} R \right).is(t) = Mc.Ar1.\varphi 10(t - \Delta t) + 0.5.Mc.Ar1.\varphi 9(t - \Delta t) + \left( L - \frac{\Delta t}{2} R \right).is(t - \Delta t) + \frac{\Delta t}{2} (vs(t) + vs(t - \Delta t)) + \left( F - D.\Delta t \right).\omega(t - \Delta t) + \frac{\Delta t}{2} \left( \tau_s(t) + \tau_s(t - \Delta t) - \tau_f(t) - \tau_f(t - \Delta t) \right) \]

\[ \theta(t) = \omega(t).t \]

\[ \{ A.X(t)\}.X(t) = B \]

\[ \{ X(t) = [\varphi 1(t) \quad \varphi 3(t) \quad \varphi 5(t) \quad \varphi 6(t) \quad \varphi 7(t) \quad \varphi 9(t) \quad \varphi 11(t) \quad is(t) \quad u1(t) \quad u2(t) \}^T \]

Equations (14) and (15), where the details are written in Refs. [21,22]. In Equation (14), the $Mc$ is the turn function of windings, and in Equation (15), the $\tau_s$, $\tau_f$, $J$, and $D$ denotes produced torque, load torque, shaft moment of inertia, and shaft damping coefficient, respectively. It is notable that the output torque in a MEC-based method is computed by the airgap Co-Energy computation as written in Equation (17) [20].

\[ \tau_c(\theta) = \frac{1}{2} \sum_{i=1}^{n_r} \sum_{j=1}^{m} (u_{1i} - u_{2j})^2 \frac{dG_b(\theta)}{d\theta} \]

5 \ | \ SIMULATION RESULTS

Simulation results are presented in this section for two following purpose.

- The machine dynamic as motor/generator for in-wheel application in the electric and hybrid vehicles.
- The machine dynamic as a 400 Hz generator for GPU application in the aircrafts.

The core non-linearity is modelled by $a = 3684$, $b = 1.027$, and $c = 0.811$ for Steel $-1010 - 2DFSO - 950$ core B - H curve fitting [24]. The above-mentioned parameters are obtained based on the actual magnetization curve after a try and error procedure. It is considerable that the proposed function in Eq. (2) is a flexible technique for various B - $\mu_s$ curve fitting based on the actual material curve (see Figure 5). It is notable that, $\Delta t = 25 \mu s$ is used as the time step in the solving procedure.

5.1 \ | \ OR-FSPM as in-wheel motor

Two different machines with tabulated parameters in Table 3 are considered for simulation, where a 44-pole/48-slot (44/48) and a 28-pole/36-slot (28/36) OR-FSPM machines are considered. It is notable that the synchronous value is the rotational speed in these machines which can be defined by

\[ Ars.u1 + Arr.u2 = Ar2.Ar1.\varphi 11 + Ar2.Ar1.\varphi 9 + Ar3.\varphi 7 - Ar4.\varphi 6 \]
Table 3: Properties of simulated OR-FSPM machines as motor/generator

| Parameter                               | Value |
|-----------------------------------------|-------|
| Outer radius of rotor (cm)              | 13.5  |
| Inner radius of rotor (cm)              | 11.5  |
| Outer radius of stator (cm)             | 11.45 |
| Inner radius of stator (cm)             | 7.45  |
| Air-gap length (mm)                     | 0.5   |
| Machine length (cm)                     | 15    |
| Arc of PMs (Deg)                        | 2.045 |
| Arc of magnetic materials (Deg)         | 2.045 |
| Arc of nonmagnetic materials (Deg)      | 2.045 |
| Stator teeth arc (Deg)                  | 5     |
| Stator slot opening arc (Deg)           | 2.5   |
| Residual flux of the PMs (T)            | 1.1   |
| Number of stator slots                  | 48    |
| Number of turns per coil                | 13    |
| Number of PMs in the rotor              | 22    |
| Resistance of stator phases (Ω)         | 0.25  |
| Line stator nominal voltage (rms)       | 380   |
| Windings connection                     | Y     |
| Nominal input frequency (Hz)            | 200   |
| Rotor inertia (kg.m²)                   | 0.125 |
| Rotor damping (N.m.s/rad)               | 0.0001|
| Rated power (kW)                        | 23    |
| Rated speed (rpm)                       | 545.45|
| Rated current (rms)                     | 30    |

| Considered parameters for modelling accuracy | Value |
|-----------------------------------------------|-------|
| Number of flux tubes in PMs                   | 2     |
| Number of flux tubes in magnetic material     | 2     |
| Number of flux tubes in non-magnetic material | 2     |
| Number of flux tubes in stator tooth          | 2     |

Equation (18) [19], where \( f_s \) and \( p \) are the frequency of induced voltages and the number of poles, respectively. Now, various scenarios are considered for simulations.

\[
\omega = \frac{2\pi f_s}{n_{pm}} = \frac{4\pi}{p f_s} (\text{rad/s}) \quad \text{and} \quad n = \frac{120}{p f_s} (\text{rpm})
\]  

5.1.1 Transient performance

Dynamic response of machines is studied in this part. Since the machine drive is not investigated, the synchronous values (545.45, and 1285.6 for 44/48, and 28/36 machines, respectively) are considered as initial speeds for both machines. Moreover, the initial rotor position (\( \theta_0 \)) is manually tuned for short transient duration time. Mechanical load torque written in Equation (19) is considered for the simulated manoeuvres (Figure 6).

\[
\tau_l = \begin{cases} 
0.1 \omega(t)^2 & \text{for 44/48 machine} \\
0.002 \omega(t)^2 & \text{for 28/36 machine} 
\end{cases}
\]  

The torque, speed, and stator currents for both machines are shown in Figure 6a,b. Moreover, the obtained B-H curve for a given flux tube (first flux tube in eighth zone), and the air-gap flux density at a sample moment for 28/36 machine are shown in Figure 6c. As can be seen in Figure 6c, the saturation effect is modelled with acceptable accuracy, hence the non-linear B-H curve for the considered element is observable. Moreover, the air-gap flux density of the 28-pole machine is shown in the figure. However, the space and time harmonics effects are visible in the air-gap flux, but a 28-pole sinusoidal component is obtained as fundamental component.

5.1.2 Steady-state characteristic

Steady-state torque and power of the machines are obtained based on various initial rotor position (\( \theta_0 \)). In all cases, the constant synchronous value is considered as rotor speed and the written input voltages in Equation (14) are considered as Equation (20).

\[
v_s = \begin{bmatrix} 
\psi_m \cos(\omega_s t) \\
\psi_m \cos(\omega_s t - 2\pi/3) \\
\psi_m \cos(\omega_s t + 2\pi/3) 
\end{bmatrix}
\]  

\[
\begin{cases} 
\psi_m = 220, \quad \omega_s = 2\pi \times 300 & \text{for 28/36} \\
\psi_m = 311, \quad \omega_s = 2\pi \times 200 & \text{for 44/48} 
\end{cases}
\]

As can be seen in Figure 7, 23 and 5.4 kW are obtained as the rated power for 44 and 28 poles machines, respectively. It is important to note that the 28-pole machine dimensions are small compared with the 48-pole type. Therefore, the rated power is obtained less for the 28-pole machine compared with the 48-pole type.

5.2 OR-FSPM as GPU

GPU is another suggestion of OR-FSPM machine usage which is proposed in this research for first time. It is shown that the
FIGURE 7  Steady-state torque and power curves based on the rotor initial position under synchronous speed

TABLE 4  Properties of simulated 44/48 OR-FSPM machine as a 400 Hz, 120 V/phase GPU

| Parameter                                      | Symbol | Value |
|------------------------------------------------|--------|-------|
| Outer radius of rotor (cm)                    | \( r_{\text{ro}} \) | 18    |
| Inner radius of rotor (cm)                    | \( r_{\text{ri}} \) | 16.5  |
| Outer radius of stator (cm)                   | \( r_{\text{so}} \) | 15.45 |
| Inner radius of stator (cm)                   | \( r_{\text{si}} \) | 10.95 |
| Air-gap length (mm)                           | \( \delta \) | 0.5   |
| Machine length (cm)                           | \( l \) | 23.5  |
| Arc of PMs (Deg)                              | \( \beta_{\text{p}} \) | 2.045 |
| Arc of magnetic materials (Deg)               | \( \beta_{\text{m}} \) | 2.045 |
| Arc of non-magnetic materials (Deg)           | \( \beta_{\text{n}} \) | 2.045 |
| Stator teeth arc (Deg)                        | \( \tau_{\text{t}} \) | 5     |
| Stator slot opening arc (Deg)                 | \( \tau_{\text{s}} \) | 2.5   |
| Residual flux of the PMs (T)                  | \( B_{\text{r}} \) | 1     |
| Number of stator slots                        | \( n_{\text{ts}} \) | 48    |
| Number of turns per coil                      | \( N_{\text{i}} \) | 2     |
| Number of PMs in the rotor                    | \( n_{\text{pm}} \) | 22    |
| Resistance of stator phases (\( \Omega \))    | \( R_{\text{s}} \) | 0.01  |
| Windings connection                           | —      | Y     |
| Rated power (kW)                              | \( P_{\text{rate}} \) | 28    |
| Rated speed (rpm)                             | \( n_{\text{rate}} \) | 1091  |
| Rated output current (rms)                    | \( I_{\text{rate}} \) | 100   |

Considered Parameters for Modelling Accuracy

| Parameter                                      | Symbol | Value |
|------------------------------------------------|--------|-------|
| Number of flux tubes in PMs                    | \( n_{1} \) | 2     |
| Number of flux tubes in magnetic material      | \( n_{2} \) | 2     |
| Number of flux tubes in non-magnetic material | \( n_{3} \) | 2     |
| Number of flux tubes in stator tooth           | \( n_{t} \) | 2     |

FIGURE 8  General schema of OR-FSPM machine usage as GPU

(a) Output voltage under full load case and \( n = 1091 \text{ rpm} \). (b) Phases currents under \( R_{\text{L}} = 1.25 \Omega \) and \( L_{\text{L}} = 0 \) and \( n = 1091 \text{ rpm} \). (c) Phase voltage under various ohmic loads.

FIGURE 9  Characteristics of the 44/48 OR-FSPM machine as GPU under various ohmic loads. (a) Voltage curves in both full load and no-load cases; (b) current and input power in full-load case; and (c) voltage and power curves.
machine can be used as a 400 Hz generator with acceptable voltage regulation. Therefore, performance of the 44/48 machine is analysed as a 120 v, 400 Hz generator under various loading cases. The machine parameters are listed in Table 4, and general schema of the machine usage as a GPU is shown in Figure 8. A three-phase RL branch is considered as the electrical load. Considering \( \mathbf{v}_0 = \mathbf{0} \), the written \( \mathbf{R} \) and \( \mathbf{L} \) matrices in Equation (14) should be defined as Equation (21), where \( L_n = 10,000 \text{ H} \) is used in Equation (21a) for \( Y \) connection modelling of the stator windings [21,22]. Simulation results of the designed GPU under various ohmic loads and \( n = 1091 \text{ rpm} \) are shown in Figure 9.

\[
\mathbf{L} = \begin{bmatrix}
L_n + L_L & L_n & L_n \\
L_n & L_n + L_L & L_n \\
L_n & L_n & L_n + L_L
\end{bmatrix}
\]

(21a)

\[
\mathbf{R} = \begin{bmatrix}
R_a + R_L & 0 & 0 \\
0 & R_a + R_L & 0 \\
0 & 0 & R_a + R_L
\end{bmatrix}
\]

(21b)

Figure 9a shows the output phases voltages under no-load and full load cases. Moreover, the windings currents and machine input power are shown in Figure 9b. In addition, the curves of the output voltage and machine power under various ohmic loads are shown in Figure 9c. As can be observed in Figure 9ab, three-phase 400 Hz voltage is produced as the GPU output voltage. Moreover, in Figure 9c, 5.3% voltage regulation is obtained. To evaluating of the designed GPU performance under RL load, two sample loading cases with fixed \( |Z| = \sqrt{R^2 + L^2 \omega^2} = 5 \) are considered in the next evaluation. Simulations are performed with two different load branches. Once, with \( R = 5 \Omega, L = 0\text{H} \), and the other under \( R = 2.5 \Omega, L = 100\mu\text{H} \) load branches which means to 5 \( \Omega \) loading with 1, and 0.707 power factors, respectively. The results are shown in Figure 10, where lower voltage amplitude is obtained with RL load.

**FIGURE 10** Voltage, current, and input power of machine under |\( Z| = 5 \Omega \) as a sample loading case with \( R \) and RL loading

**FIGURE 11** Performed simulations by 2D- and 3D-FEM. (a) Mesh plot and flux density at 100 ms in 3D-FEM; (b) speed curve during 100 ms; and (c) flux density at \( t = 100 \text{ ms} \) in 2D-FEM

### 5.3 Validation and comparison by 3D- and 2D-FEM

For validation of the performed simulations, 3D and 2D, FEM-based analyses are performed by the Ansoft/Maxwell software. The 44/48 OR-FSPM machine with listed parameters in Table 3 is modelled, and the results are compared in terms of processing duration time and methods accuracy. It is notable that the half symmetrical model in the \( xy \) surface is used for both 2D and 3D analyses, where half axial symmetry is additionally applied for 3D-FEM model, as shown in Figure 11a,c. The 0.25 mm inside-selection and on-selection length-based Mesh are used for 2D- and 3D-FEM, respectively, where \( \Delta t = 25 \mu\text{s} \) is used for both
TABLE 5 Comparison of performed simulations time by MEC an FEM

|        | MEC  | 3D-FEM | 2D-FEM |
|--------|------|--------|--------|
| 4.3 h  | 156.6 h | 26.1 h |

Simulation time improvement using MEC compared with FEM

- Compared with 2D-FEM: 83.5%
- Compared with 3D-FEM: 97.2%

are shown. Figure 11c shows the flux density at a sample moment in 2D environment. Moreover, comparison between the obtained results by the used MEC method and the 3D-FEM is performed in Figure 12a, where the speed, torque, and windings currents under the defined load torque in Equation (22) are compared. Moreover, to analysis of the proposed method capability in the saturation model, the obtained B-H curve for a sample flux tube are compared. Figure 12b shows the actual B-H curve of the used material (Steel-1010-2DFS0-950), which is presented for the mentioned core in Ansoft/Maxwell as well as the obtained curve for $R_{81}$ is compared in Fig. 12c, where one half of the steady-state $R_{81}$ is considered. Noticing to the results, there are acceptable agreement between the obtained results. The processing time duration for 10 ms simulation is tabulated in Table 5, where very shorter processing time is obtained by the MEC compared with both 2D-FEM and 3D-FEM.

6 | CONCLUSION

In this research, a known flexible MEC method is represented for a novel OR-FSPM machine model for first time. The machine performance for in-wheel applications in the EV and HEVs is analysed as well as the machine capability for GPU application is studied, where the machine performance as a 400 Hz generator is introduced. Saturation effect is modelled by a novel method, where the B-H curve of all the materials can be tuned by selective parameters. As a considerable paper novelty, the presented method can be used for all the OR-FSPM machines with various properties and dimensions. Moreover, the model accuracy can be tuned for a given machine simulation. Performed validation by 2D and 3D FEM-based analyses showed the model accuracy, whereas very shorter processing time is obtained by MEC.

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APPENDIX A

Some details of the MEC-based equations (Equations (3)-(13)) are written as follows, where the others can be understood by the written equations:

For $i = 1,3,5$ ($R_1, R_3,$ and $R_5$):

$$R_i = \begin{bmatrix} 0 & R_1 & 0 & \ldots & 0 & 0 \\ 0 & 0 & R_2 & \ldots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ R_1 & 0 & \ldots & 0 & 0 \\ \end{bmatrix} \quad (23A)$$

For $i = 2,4$ ($R_2$ and $R_4$):

$$R_i = \begin{bmatrix} -R_1 & R_2 & 0 & \ldots & 0 & 0 \\ 0 & -R_2 & R_3 & 0 & \ldots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ R_1 & 0 & \ldots & 0 & -R_5 \end{bmatrix} \quad (24A)$$

$$R_6 = \begin{bmatrix} R_6_{11} & 0 & 0 & \ldots & 0 & 0 \\ 0 & R_6_{22} & 0 & \ldots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \ldots & 0 & R_6_{nn} \end{bmatrix} \quad (25A)$$

$$R_9 = \begin{bmatrix} 0 & R_9_{22} & 0 & \ldots & 0 & 0 \\ 0 & 0 & R_9_{33} & 0 & \ldots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \ldots & 0 & 0 \end{bmatrix} \quad (26A)$$

$$R_{10} = \begin{bmatrix} -R_{10_{11}} & R_{10_{12}} & 0 & \ldots & 0 & 0 \\ 0 & -R_{10_{22}} & R_{10_{33}} & 0 & \ldots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ R_{10_{11}} & 0 & \ldots & 0 & -R_{10_{nn}} \end{bmatrix} \quad (27A)$$

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Details of Equations (12) and (10) are written in Equations (32A) and (33A), respectively.

\[
\begin{align*}
\text{As}_1 &= \begin{bmatrix}
1 & -1 & 0 & \ldots & \ldots & 0 & 0 \\
0 & 1 & -1 & 0 & \ldots & 0 & 0 \\
\vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots \\
-1 & 0 & \ldots & \ldots & 0 & 1
\end{bmatrix} \\
\text{As}_r &= \text{As}_s^T = \begin{bmatrix}
G_{11} & G_{12} & \ldots & \ldots & G_{1,ns} \\
G_{21} & G_{22} & \ldots & \ldots & G_{2,ns} \\
\vdots & \ddots & \ddots & \ddots & \ddots \\
G_{nr,1} & G_{nr,2} & \ldots & \ldots & G_{nr,ns}
\end{bmatrix}
\end{align*}
\]

\[
\text{As}_s = \sum_{j=1}^{m} G_{ij} 0 0 \ldots 0 \\
\text{Ass} = \begin{bmatrix}
0 & \sum_{j=1}^{m} G_{ij} & 0 & \ldots & 0 \\
\vdots & \ddots & \ddots & \ddots & \ddots \\
0 & \ldots & 0 & \sum_{j=1}^{m} G_{nr,j}
\end{bmatrix}
\]

\[
\text{Ar}_r = \sum_{j=1}^{nr} G_{j1} 0 0 \ldots 0 \\
\text{Arr} = \begin{bmatrix}
0 & \sum_{j=1}^{nr} G_{j1} & 0 & \ldots & 0 \\
\vdots & \ddots & \ddots & \ddots & \ddots \\
0 & \ldots & 0 & \sum_{j=1}^{nr} G_{j,ns}
\end{bmatrix}
\]

\[
\begin{cases}
-R_{7_{ns}} \varphi_{7_{ns}} - R_{8_{1}} \varphi_{8_{1}} - 0.5 F_s + R_{9_{2}} \varphi_{9_{2}} + R_{8_{2}} \varphi_{8_{2}} = R_{6_{nt}} \varphi_{6_{nt}} \\
-R_{8_{2}} \varphi_{8_{2}} - 0.5 F_s + R_{9_{3}} \varphi_{9_{3}} + R_{8_{3}} \varphi_{8_{3}} + R_{7_{nt+1}} \varphi_{7_{nt+1}} = R_{6_{nt+1}} \varphi_{6_{nt+1}} \\
-R_{8_{2nt}} \varphi_{8_{2nt}} - 0.5 F_s + R_{9_{1}} \varphi_{9_{1}} + R_{8_{1}} \varphi_{8_{1}} + R_{7_{1}} \varphi_{7_{1}} = R_{6_{ns}} \varphi_{6_{ns}}
\end{cases}
\]

Considering \( \varphi_8 = \text{As}_1 \varphi_9 + \text{As}_1 \varphi_{11} \rightarrow R_7 \varphi_7 + R_8 \text{Ar}_1 \varphi_{11} + (R_9 + \text{Ar}_1 \text{R}_8) \varphi_9 - 0.5 F_s = R_6 \varphi_6 
\]

\[
\begin{cases}
\varphi_{8_1} = \varphi_{7_1} + \cdots + \varphi_{7_{nt}} \\
\varphi_{8_2} = -\varphi_{6_{nt}} + \varphi_{6_{nt+1}} \\
\varphi_{8_3} = \varphi_{7_{nt+1}} + \cdots + \varphi_{7_{2nt}} \\
\varphi_{8_4} = -\varphi_{6_{2nt}} + \varphi_{6_{2nt+1}} \\
\vdots
\end{cases}
\]

Considering \( \varphi_8 = \text{As}_1 \varphi_9 + \text{As}_1 \varphi_{11} \rightarrow \text{Ar}_5 \text{Ar}_1 \varphi_{11} + \text{Ar}_5 \text{Ar}_1 \varphi_9 = \text{Ar}_6 \varphi_7 
\]
APPENDIX B

Procedure of the equation solving is illustrated as below algorithm.

**Algorithm 1** Solving equations by Newton–Raphson method

**Data**: Constant data and constant matrices include:

nts, ns, nr, nt, Atj, lj

Compute: \( G_{ij}(\theta) \), Me, We;

Compute: \( \text{As}1, \text{Ar}1, \text{Ar}2, \text{Ar}3, \text{Ar}4, \text{Ar}5, \text{Ar}6 \)

**Result**: Solving equations

initialization;

\( t = 0, \Delta t = 29\mu s, T_{\text{max}} = 0.25s, X(t = 0) = 0 \)

Initial secondary position: \( \theta(t = 0) \)

Acceptable error: \( \varepsilon_r = 1 \times 10^{-8} \)

Maximum iteration number: \( k_{\text{max}} \)

while \( t \leq T_{\text{max}} \) do

initialization for Newton-Raphson;

Iteration index: \( k = 1 \)

\( X(t)^{(0)} = X(t - \Delta t) \)

Compute: \( \text{As} \left( \theta(t) \right), \text{Ar} \left( \theta(t) \right), \text{Ars} \left( \theta(t) \right) \)

while \( k \leq k_{\text{max}} \) do

Compute: \( \text{R}11 \left( X(t)^{(k-1)} \right) \)

Compute: \( A \left( X(t)^{(k-1)} \right), B; \)

Compute: Jacobian matrix, \( J \left( X(t)^{(k-1)} \right); \)

Compute: \( \Delta f = B - A \left( X(t)^{(k-1)} \right) . X(t)^{(k-1)} \)

Compute: \( \Delta X(t)^{(k)} = J \left( X(t)^{(k-1)} \right)^{-1} . \Delta f \)

if \( \text{Max} \left( \Delta X(t)^{(k)} \right) \leq \varepsilon_r \) then

\( X(t)^{(k)} = X(t)^{(k-1)} \)

Compute: \( \tau_s(t) \) by Eq. (17)

Compute: \( \omega(t), \theta(t) \) by Eq. (15)

\( t = t + \Delta t \)

else

\( k = k + 1 \)

\( X(t)^{(k)} = X(t)^{(k-1)} + \Delta X(t)^{(k)} \)

end

end

\( X(t) = X(t)^{(k)} \)