

AVERAGED MODEL OF DCMGS WITH PV ARRAYS FOR TRACTION SUBSTATION IN HEAVY RAIL SYSTEMS

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Abstract

This paper presents the mathematical model of DCMGs with PV arrays for traction substations in heavy rail systems. The considered power system consists of many power converters in which the dynamic model is time-varying due to the switching actions inside the power converters. The time-varying model is not usable for system analysis and design. Hence, this paper describes how to derive the time-invariant model using the combination of DQ and GSSA methods. The simulation results using the SimPowerSystem® block set on MATLAB are used to validate the proposed model. The results show that the proposed model can provide accurate transient and steady-state responses. Moreover, simulations using the proposed model can reduce the simulation time by 72% compared to the exact topological model of MATLAB. The resulting averaged models are also beneficial for studies of the dynamic behavior of complex power systems.

Keywords: Averaged model; DC micro-grid; DQ method; GSSA method; heavy rail systems

Introduction

Nowadays, the electrical railway system has increased because of the expansion of the urban society population. In Thailand, the Metropolitan Rapid Transit (MRT) mass rapid transit systems serve the Bangkok metropolitan region in which almost of all systems are heavy railways that can accommodate many passengers (Kingmaneerat *et al.*, 2023). As for heavy railways, the twelve-pulse diode rectifier is used for the conventional electrical system to convert the alternating current

(AC) to direct current (DC). However, it is not flexible to connect with renewable energies as well as the regenerative braking from the trans. In this paper, the bi-directional voltage source converter (VSC) or PWM rectifier is introduced. The conventional rectifier will be replaced with the bi-directional PWM rectifier in which the power flow between the AC source and the DC bus can be allowed (Pakdeeto *et al.*, 2017). Thus, the PV arrays or other renewable energies can be connected to

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the conventional system via the PWM rectifier as well as the regenerative braking from the electric train. The considered electrical power system in this paper can be called the direct current micro-grid system (DCMG) (Kumar *et al.*, 2015; Pakdeeto *et al.*, 2021). There are a lot of power converters inside the heavy rail systems such as the PWM rectifiers and the inverters of traction motor drive systems. The behavior of controlled power converters acts as the negative impedance called “constant power loads (CPLs)” (Cespedes *et al.*, 2011; Rivetta *et al.*, 2005). These loads can degrade the system stability. Therefore, the stability analysis is very important. For stability analysis, the accurate mathematical model is very crucial (Hong *et al.*, 2019; Phosung *et al.*, 2021). Furthermore, these models are not only used for analyzing system stability, but they are also used for studies of dynamic behavior of complex power systems with the fast computational time (Ngamkong *et al.*, 2012).

Generally, the mathematical models of power converters are time-varying due to the switching functions. It is complicated to use these models for stability studies. Moreover, the time-varying model uses the huge computational time for simulation. From the literature reviews (Areerak *et al.*, 2008; Emadi, 2001; Ngamkong *et al.*, 2012; O’Rourke *et al.*, 2019), the direct quadrature (DQ) method and the generalized state-space averaging approach (GSSA) are suitable for deriving the model of the three-phase power converters and DC-to-DC power converters, respectively. Therefore, in this paper, the DQ method is used to eliminate the switching action of bi-directional PWM rectifier, while the GSSA method is used for analyzing the boost converter including the maximum power point tracking (MPPT) algorithm. As a result, the time-invariant model of the proposed heavy rail systems can be obtained. The exact topological model from MATLAB is used to validate the proposed averaged model.

The main advantages in this research are as follows:

- The details how to derive the time-invariant model by the combination between the DQ and GSSA methods are presented.
- The bi-directional VSC to replace the conventional diode rectifier is presented to support renewable energies and the regenerative braking in the future
- The DC bus voltage is regulated by the bi-directional VSC as the constant value. It is different from the conventional diode rectifier in which the DC bus voltage is not controlled.
- The proposed model can provide accurate responses with the faster computational time

compared with the exact topological model in MATLAB.

This paper is structured in five sections as follows: The first section is the introduction. The second section is the considered system. The details how to derive the time-invariant mathematical model are addressed in the third section. The model validation using the exact topological model in MATLAB is presented in the fourth section. Finally, the fifth section is the conclusion.

Considered System

In this paper, the novel heavy rail system represented by the DCMGs with PV arrays is illustrated in Figure 1. The considered system consists of three parts as follows: The first part is the main power from the Metropolitan Electricity Authority (MEA) of Thailand feeding the substation. In the substation, the power can be divided into two ways which are the traction system and depot passenger station. The second part is the traction load system where the amounts of trains equal to two are maximum per station. The traction loads behave as a CPL. The last part is the PV arrays including the MPPT algorithm used to track the maximum power at any irradiances. As for the second part, the twelve pulses diode rectifier of the conventional system are replaced by the bi-directional VSC which has the cascade PI controllers for the DC bus voltage regulation. However, the depot passenger station that is used to operate as the control center as shown in Figure 1 (grey area) is not focused in this paper. Therefore, the equivalent circuit of the considered system is depicted in Figure 2 in which the PI controller is used to regulate the DC link voltage. The PI controller is designed based on the coefficient

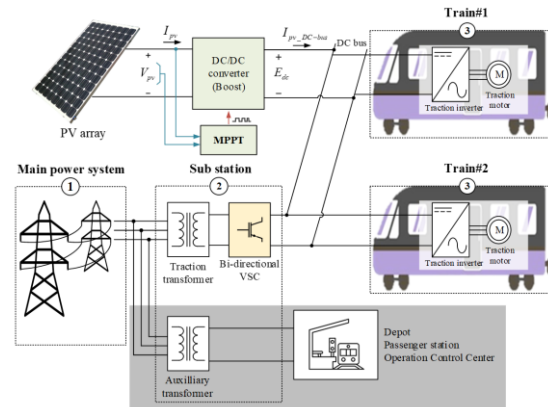


Figure 1. Heavy rail system

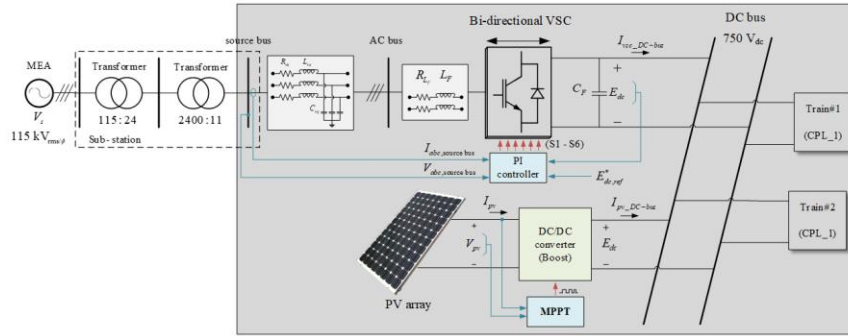


Figure 2. Considered system

comparison with the standard second order system transfer function. However, this paper focuses on only how to derive the time-invariant model using the proposed averaging method. The controller design process is not considered in the paper. The results will show that the proposed model can provide the accurate response compared with those from the exact topology model of MATLAB. The main assumption for the model derivation is that the system has to be operated under the continuous conduction mode (CCM).

$$[\mathbf{f}_{dq0}] = [\mathbf{T}_{dq0}][\mathbf{f}_{abc}] \quad (1)$$

where

$$[\mathbf{T}_{dq0}] = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin \theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

Mathematical Model Derivation

This section describes the details of how to derive the mathematical model of DCMGs with PV arrays for traction substation in heavy rail systems as shown in Figure 2. However, from this figure, the MEA source will supply the load through the transformer with the voltage ratio. For the derivation, the ideal three-phase voltage source is used to represent the voltage at the source bus by ignoring the dynamic behaviors of the transformers. In this paper, the combination between DQ and GSSA methods will be used to eliminate the time variable, resulting in a time-invariant model.

DQ Method

The DQ method is based on the Park's transformation. This transformation is used to convert the three-phase functions into the D and Q axes. These axes are the rotating frames in which the angular velocity is related to the frequency of three-phase functions as shown in Figure 3.

From Figure 3, the D and Q axes are always perpendicular, and they always rotate at the same frequency as the three-phase function. The result of this technique is that the values on the D and Q axes will be constant similarly to the DC components. The three-phase variables are converted into these axes that can be calculated with Equation 1 (O'Rourke *et al.*, 2019).

After the DQ method is applied, the equivalent circuit of the three-phase power system of the considered system will be the DC circuit. Moreover, the bi-directional VSC can be modeled into the ideal power transformer (Pakdeeto *et al.*, 2017) as shown in Figure 4 where the time variable of the switching function from this rectifier will not appear in the model. In Figure 4, the controllers are still not considered in this step. In addition, the PV arrays will be replaced with the ideal DC-current source (Izadian *et al.*, 2012). As for the equivalent circuit in Figure 4, it is very simple to obtain the set of differential equations using the basic circuit theory.

In this paper, the source bus voltage level can be calculated by the MEA voltage multiplying the turn ratio of transformers. The source bus voltage (V_s) will be equal to 110 V_{rms}. Hence, the ideal voltage source equal to 110 V_{rms/phase} can be used to represent the main power supply of the heavy rail systems. The voltage source in d-q axes can then be

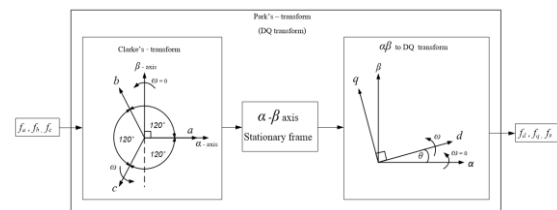


Figure 3. DQ transformation diagram

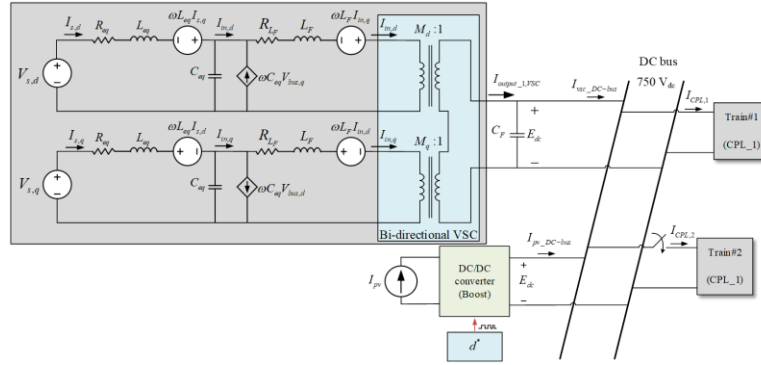


Figure 4. Equivalent circuit on D-Q axes of the considered system

calculated with Equation 2 in which the diagram of axes rotating can be depicted in Figure 5. The V_i and $\hat{M}_k$ as seen in Figure 5 are the terminal voltage and vectors of modulation index of the bi-directional VSC, respectively.

$$\begin{bmatrix} V_{s,d} \\ V_{s,q} \end{bmatrix} = \sqrt{\frac{3}{2}} \begin{bmatrix} V_m \cos(\phi - \phi_1) \\ V_m \sin(\phi - \phi_1) \end{bmatrix} \quad (2)$$

where V_m is the peak voltage of V_s . The ϕ and ϕ_1 are the source bus angle and angle rotation of the DQ-axis, respectively.

GSSA

The GSSA will be applied to the DC-to-DC power converters to eliminate the switch function of boost converters. Generally, the switching function of DC-to-DC power converters is periodic as depicted in Figure 6. It is well-known that the periodic function can be represented with complex Fourier series as calculated in Equation 3 (Emadi, 2001) where the ω_s is equal to $2\pi / T_s$.

$$f(t) = \sum_{k=-\infty}^{\infty} \langle x \rangle_k(t) e^{jk\omega_s t} \quad (3)$$

From Equation 3, the $\langle x \rangle_k(t)$ is the complex Fourier coefficients that can be calculated in Equation 4, while k is the harmonic order and T_s is the switching period.

$$\langle x \rangle_k(t) = \frac{1}{T} \int_{t-T}^t f(t) e^{-jk\omega_s t} dt \quad (4)$$

As for the switching function $u(t)$, it can be calculated in Equation 5 when the k is set to 0 under the zero-order approximation. For this approximation, the higher-order harmonics are not considered. It is sufficient for this research work

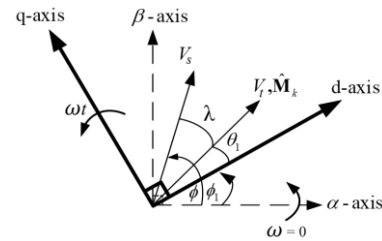


Figure 5. Axes rotation diagram

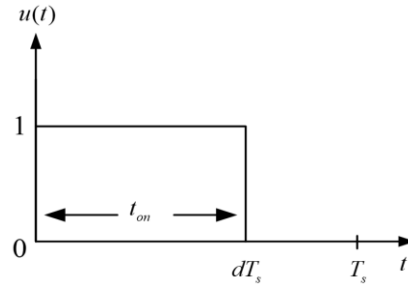


Figure 6. Switching function of DC-to-DC power converters

because the harmonic does not affect the controller design or system stability (Pakdeeto *et al.*, 2017).

$$\begin{aligned} \langle u \rangle_0 &= \frac{1}{T_s} \int_0^{T_s} u(t) \cdot e^0 dt = \frac{1}{T_s} \int_0^{T_s} 1 dt \\ \langle u \rangle_0 &= d \end{aligned} \quad (5)$$

where the d is the duty cycle of power converter equal to t_{on} / T_s .

PI Controller

The cascade PI controllers is used to regulate the DC bus voltage as a constant value by controlling the bi-directional VSC. The block diagram of the controller is illustrated in

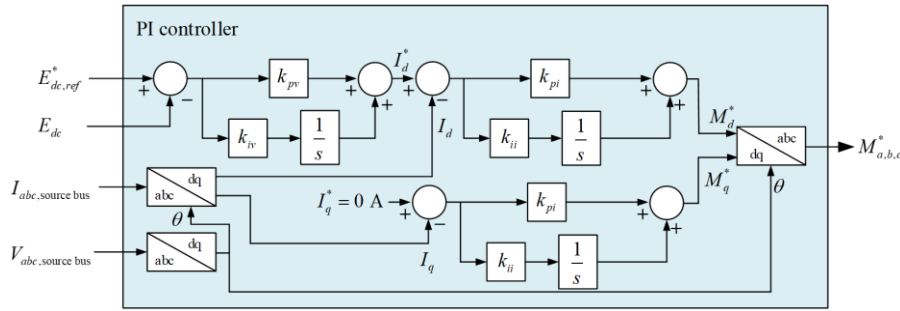


Figure 7. PI controller diagram

Figure 7 where the M_d^* and M_q^* can be calculated in **MPPT** Equation 6.

$$\begin{aligned} M_d^* &= \frac{1}{A_r} \left(E_{dc}^* K_{pv} K_{pi} - E_{dc} K_{pv} K_{pi} + X_v K_{iv} K_{pi} \right) \\ M_q^* &= \frac{1}{A_r} \left(-I_{in,d} K_{pi} + X_{id} K_{ii} \right) \end{aligned} \quad (6)$$

In addition, this controller can allow the power flow between the DC bus and the MEA source. When the power from the auxiliary source (PV) exceeds the load requirements, the remaining power can supply the MEA through the bi-directional VSC. On the other hand, the power can be supplied to the load with the combination of MEA source and PV arrays, resulting in more reliability.

This paper proposed that the PV arrays are the auxiliary source of the considered system. The characteristics of the PV arrays can be illustrated in Figure 8 which is the general relation between power-voltage (P-V) and current-voltage (I-V) of the PV arrays. These curves show the maximum power point (MPP) and it depends on the irradiance falling on the PV panels. To obtain the maximum power at any irradiance, the MPPT using the perturbation and observation (P&O) algorithm is applied (Abdelsalam *et al.*, 2011; Boukenoui *et al.*, 2015). In this paper, it is assumed that the dynamic of the P&O algorithm is very fast compared with the dynamic of the whole system. Thus, the d^* is set to the constant for each irradiance, and the d^* can be calculated by Equation 7.

$$d^* = 1 - \frac{V_{mpp}}{E_{dc}^*} \quad (7)$$

$$I_{pv} = N_p \left[\left(I_{s,c} + K_i (T - T_{ref}) \right) \left(\frac{G}{G_{ref}} \right) \right] - \left[\left(\frac{I_{s,c}}{e^{\left(\frac{V_{sc}}{n_s V_T} \right)} - 1} \right) \left(\frac{T}{T_{ref}} \right)^3 \left(e^{\left(\frac{T}{T_{ref}} \right) \left(\frac{E_g}{n_s V_T} \right)} \right) \left(e^{\left(\frac{V_{sc}}{n_s V_T} \right) \left(\frac{I_{sc} R_s}{n_s V_T} \right)} - 1 \right) \right] \quad (8)$$

$$\begin{cases} \dot{I}_{s,d} = -\frac{R_{eq}}{L_{eq}} I_{s,d} + \omega I_{s,q} - \frac{1}{L_{eq}} V_{bus,d} + \frac{1}{L_{eq}} V_{s,d} \\ \dot{I}_{s,q} = -\omega I_{s,d} - \frac{R_{eq}}{L_{eq}} I_{s,q} - \frac{1}{L_{eq}} V_{bus,q} + \frac{1}{L_{eq}} V_{s,q} \\ \dot{V}_{bus,d} = \frac{1}{C_{eq}} I_{s,d} + \omega V_{bus,q} - \frac{1}{C_{eq}} I_{in,d} \\ \dot{V}_{bus,q} = \frac{1}{C_{eq}} I_{s,q} - \omega V_{bus,d} - \frac{1}{C_{eq}} I_{in,q} \\ \dot{I}_{in,d} = \frac{1}{L_f} V_{bus,d} - \frac{R_{lf}}{L_f} I_{in,d} + \omega I_{in,q} - \frac{K_{pv} K_{pi} E_{dc}^* E_{dc}}{A_f L_f} + \frac{K_{pv} K_{pi} E_{dc} E_{dc}}{A_f L_f} - \frac{K_{iv} K_{pi} E_{dc} X_v}{A_f L_f} + \frac{K_{pi} I_{in,d} E_{dc}}{A_f L_f} - \frac{K_{ii} E_{dc} X_{id}}{A_f L_f} \\ \dot{I}_{in,q} = \frac{1}{L_f} V_{bus,q} - \omega I_{in,d} - \frac{R_{lf}}{L_f} I_{in,q} + \frac{K_{pv} K_{pi} E_{dc} E_{dc}}{A_f L_f} - \frac{K_{iv} K_{pi} E_{dc} X_v}{A_f L_f} - \frac{K_{pi} I_{in,d} E_{dc}}{A_f L_f} + \frac{K_{ii} E_{dc} X_{iq}}{A_f L_f} \\ \dot{E}_{dc} = \frac{K_{pv} K_{pi} E_{dc}^* I_{in,d}}{A_f C_f} + \frac{K_{pv} K_{pi} E_{dc} I_{in,d}}{A_f C_f} + \frac{K_{iv} K_{pi} I_{in,d} X_v}{A_f C_f} - \frac{K_{pi} I_{in,d} I_{in,d}}{A_f C_f} + \frac{K_{ii} I_{in,q} X_{iq}}{A_f C_f} + (1-d^*) \frac{I_{L,boost}}{C_f} - \frac{P_{CPI,1}}{C_f E_{dc}} - \frac{P_{CPI,2}}{C_f E_{dc}} \\ \dot{X}_{id} = K_{pv} E_{dc} - K_{pi} E_{dc} + K_{iv} X_v - I_{in,d} \\ \dot{X}_{iq} = -I_{in,q} \\ \dot{X}_v = E_{dc}^* - E_{dc} \\ \dot{I}_{L,boost} = \frac{V_{pv}}{L_{boost}} - (1-d^*) \frac{E_{dc}}{L_{boost}} \\ \dot{V}_{pv} = -\frac{I_{L,boost}}{C_{pv}} + \frac{I_{pv}}{C_{pv}} \end{cases} \quad (9)$$

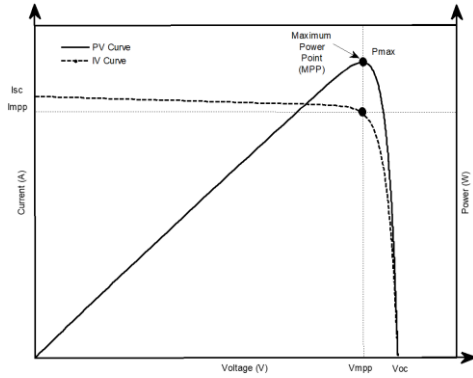


Figure 8. PV characteristics

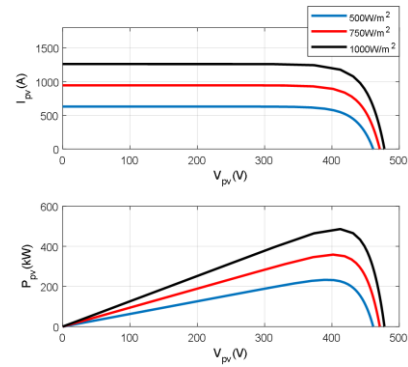


Figure 9. Considered P-V and I-V curves

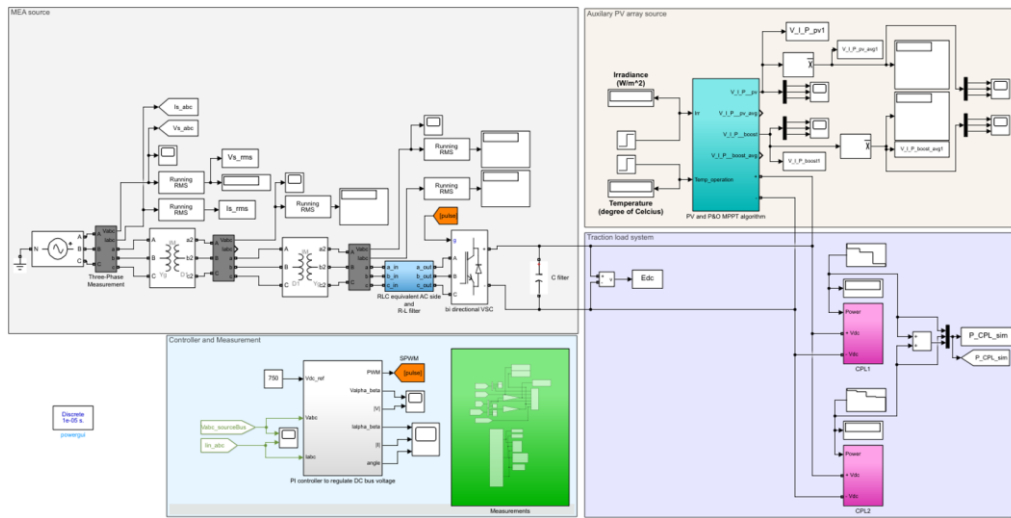


Figure 10. The exact topological model with SimPowerSystem® on MATLAB

After the DQ and GSSA methods are applied, the M_d , M_q , and d will be set equal to M_d^* , M_q^* and d^* , respectively. In addition, the I_{pv} of PV arrays can be calculated in Equation 8 in which the deep details of I_{pv} can be found in (Izadian *et al.*, 2012). The time-invariant model of the considered system can be shown in Equation 9.

Model Validation

The system parameters used for the model validation can be shown in Table 1.

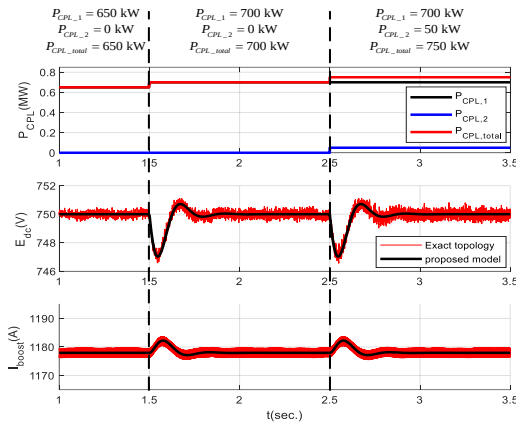
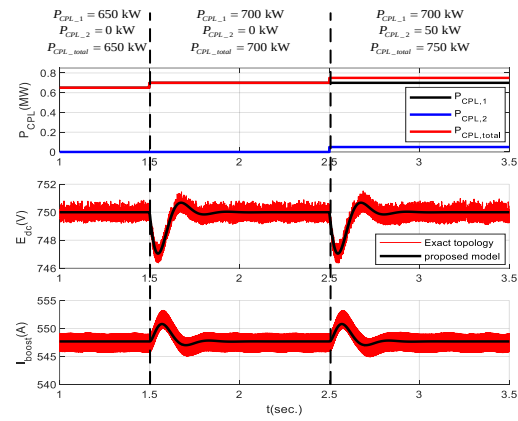
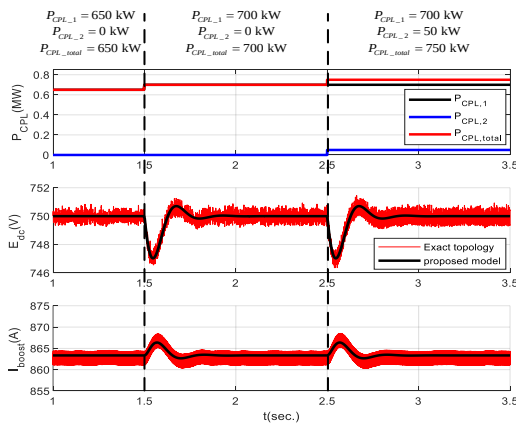
As mentioned before, the considered power system is presented to be a future choice for adding renewable energies into the conventional heavy rail system. From the literature review, rooftop areas of the consumer station of the railway system in Thailand are about 250 m × 18 m (width × length). If the PV panel (400 W) is used, its size will be approximately equal to 3 m² (Mingpruk *et al.*,

2023). Hence, number of panels are around 1,240 arrays and the maximum power is approximately equal to 496 kW at 1,000 W/m². The PV characteristics used in this paper can be illustrated in Figure 9.

From the P-V and I-V curves, the maximum powers at 1,000, 750, and 500 W/m² are approximately equal to 496, 358, and 233 kW, respectively. In addition, the currents from PV panels are equal to 1,178, 864, and 548 A in each irradiance as seen in Figure 9. To ensure the accuracy of the proposed model, the responses from the proposed mathematical model will be compared with those from the exact topological simulation as seen the overall MATLAB model in Figure 10. The model validation can be divided into 3 scenarios: the first is the irradiance equal to 1,000 W/m². For this case, the P_{CPL_total} ($P_{CPL_1} + P_{CPL_2}$) is changed from 650 kW to 700 kW and 750 kW when the t is equal to 1.5 and 2.5 s., respectively. The E_{dc} and I_{boost} responses for the first

Table 1. System parameters

Parameters	Values	Descriptions
V_s	110 V _{rms}	Voltage source obtained from MEA through transformer ratio
ω	50 Hz	System frequency
R_{eq}	1 $\mu\Omega$	Resistance of transmission line equivalent circuit
L_{eq}	10 nH	The inductance of the transmission line equivalent circuit
C_{eq}	22 nF	The capacitance of the transmission line equivalent circuit
R_{LF}	1 m Ω	The inductor's inner resistance of the filter circuit
L_F	5 μ H	Inductor value of filter circuit
C_{dc}	500 mF	Capacitor value of filter circuit
K_{pv}	44.9881	Proportional gain of the voltage loop
K_{iv}	1443.98	Integral gain of the voltage loop
K_{pi}	-0.00001	Proportional gain of the current loop
K_{ii}	-0.04000	Integral gain of the current loop

Figure 11. Model validation at the irradiance equal to 1,000 W/m²Figure 13. Model validation at the irradiance equal to 500 W/m²Figure 12. Model validation at the irradiance equal to 750 W/m²

case are depicted in Figure 11. Other scenarios are the irradiance changing while the P_{CPL_total} is the same as the first condition.

As for Figure 11, the E_{dc} is the DC bus voltage and the I_{boost} is the current through the inductor of the boost converter in which this current can be

represented as the output current from PV arrays. It can be seen in Figure 11 that the black line obtained from the proposed model is nearly the same as the exact topological model (red line) in both transient and steady state responses. In addition, the current from the PV panels is achieved at the maximum power when the irradiance is equal to 1,000 W/m². Hence, the MPPT algorithm can be used to achieve the maximum power from PV arrays. In addition, the model validations when the irradiances are equal to 750 and 500 W/m² can be shown in Figures 12 and 13, respectively.

The results in Figures 12 and 13 are the model validation when the irradiance is changed as the same load from the first scenario. The results can confirm that the proposed model is more accurate. Moreover, the results show that the DC bus voltage regulation and the maximum power can be achieved. For the model validation process, the personal computer specifications are Intel(R) Core(TM) i7-10700 CPU @ 2.90GHz, RAM 16 GB, and 64-bit operating system on Windows 10. The proposed mathematical model and the exact

topological model used 3.7801 and 13.66 min, respectively for the simulation. The comparison of simulation time can be illustrated in terms of computational time saving defined by Equation 10.

$$\%t_{\text{saving}} = \frac{t_{fs} - t_{av}}{t_{fs}} \times 100\% \quad (10)$$

where t_{fs} and t_{av} are the simulation times of the full topology and averaged models, respectively.

According to Equation 10, the proposed averaged model can provide $\%t_{\text{saving}} = 72$. It is indicated that the proposed time-invariant model requires short computational time compared with the exact topological model of MATLAB. Therefore, the proposed mathematical model is accurate and useful for future research such as optimal controller design, stability analysis, etc. Moreover, the new architecture for heavy rail traction systems are useful for the future practice.

Conclusions

This paper presents the new architecture for the traction substation in heavy rail systems and the details of how to derive the averaged model. The resulting model can be used for various system parameters. The model can provide the accurate response under the assumption that the systems have to be operated under the CCM mode. The bi-directional VSC is used to replace the diode rectifier in which it can be available to add renewable energies or regenerative braking in the future work. However, many converters are used in the considered system, resulting in the time-varying model. To eliminate the time variable and switching function, the DQ and GSSA methods are used for the three-phase power system and DC-to-DC converter, respectively. After these methods are applied, the time-invariant model is achieved. To confirm the accuracy of the proposed averaged model, the model validation using the comparison between the exact topological and proposed model responses is presented. The results confirm that the proposed model is accurate in both transient and steady-state responses. In addition, it can be used to provide the system response in any scenarios with the fast simulation time compared with the exact topological model from MATLAB. For the future research work, the proposed dynamic model can be used for the stability analysis via the control theory as well as the design process of the instability mitigation due to the constant power loads inside the rail systems.

Acknowledgments

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References

- Abdelsalam, A.K., Massoud, A.M., Ahmed, S., and Enjeti, P.N. (2011). High-performance adaptive perturb and observe mppt technique for photovoltaic-based microgrids. *IEEE Transactions on Power Electronics*, 26(4):1010-1021. <https://doi.org/10.1109/TPEL.2011.2106221>
- Areerak, K.N., Bozhko, S., Asher, G.M., and Thomas, D. (2008). DQ-transformation approach for modelling and stability analysis of ac-dc power system with controlled pwm rectifier and constant power loads. In: 2008 13th International Power Electronics and Motion Control Conference, Poznan, Poland, 2008, p. 2049-2054. <https://doi.org/10.1109/EPEPEMC.2008.4635567>
- Boukenoui, R., Bradai, R., Mellit, A., Ghanes, M., and Salhi, H. (2015). Comparative analysis of P&O, modified hill climbing-FLC, and adaptive P&O-FLC MPPTs for microgrid standalone PV system. In: 2015 International Conference on Renewable Energy Research and Applications (ICRERA), Palermo, Italy, 2015, p. 1095-1099. <https://doi.org/10.1109/ICRERA.2015.7418579>
- Cespedes, M., Xing, L., and Sun, J. (2011). Constant-power load system stabilization by passive damping. *IEEE Transactions on Power Electronics*, 26(7):1832-1836. <https://doi.org/10.1109/TPEL.2011.2151880>
- Emadi, A. (2001). Modelling and analysis of multi-converter DC power electronic systems using the generalized state space averaging method. *IECON'01. 27th Annual Conference of the IEEE Industrial Electronics Society*, (Cat. No.37243), Denver, CO, USA, 2001, 2:1001-1007. <https://doi.org/10.1109/IECON.2001.975908>
- Hong, Y., Shuai, Z., Cheng, H., Tu, C., Li, Y., and Shen, Z.J. (2019). Stability analysis of low-frequency oscillation in train-network system using rlc circuit model. *IEEE Transactions on Transportation Electrification*, 5(2):502-514. <https://doi.org/10.1109/TTE.2019.2905983>
- Izadian, A., Pourtaherian, A., and Motahari, S. (2012). Basic model and governing equation of solar cells used in power and control applications. In: 2012 IEEE Energy Conversion Congress and Exposition (ECCE), Raleigh, NC, USA, p. 1483-1488. <https://doi.org/10.1109/ECCE.2012.6342639>
- Kingmaneerat, A., Kulworawanichpong, T., and Ratniyomchai, T. (2023). Traction power substation outage and reliability evaluation for a DC mass rapid transit system. *GMSARN International Journal*, 17(4):421-428.
- Kumar, M., Srivastava, S.C., Singh, S.N., and Ramamoorthy, M. (2015). Development of a control strategy for interconnection of islanded direct current microgrids. *IET Renewable Power Generation*, 9(3):284-296. <https://doi.org/10.1049/iet-rpg.2013.0375>
- Mingpruk, N., Mongkoldee, K., Homjan, J., and Panpean, C. (2023). Utilisation of solar rooftops for energy reduction: a case study for airport rail link. In: 2023 International Electrical Engineering Congress (iEECON), Krabi, Thailand, p. 193-197. <https://doi.org/10.1109/iEECON56657.2023.10127021>

- Ngamkong, P., Kochcha, P., Areerak, K., Sujitjorn, S., and Areerak, K. (2012). Applications of the generalized state-space averaging method to modelling of DC-DC power converters. *Mathematical and Computer Modelling of Dynamical Systems*, 18(3):243-260. <https://doi.org/10.1080/13873954.2011.635377>
- O'Rourke, C.J., Qasim, M.M., Overlin, M.R., and Kirtley, J.L. (2019). A geometric interpretation of reference frames and transformations: dq0, clarke, and park. *IEEE Transactions on Energy Conversion*, 34(4):2070-2083. <https://doi.org/10.1109/TEC.2019.2941175>
- Pakdeeto, J., Areerak, K., and Areerak, K. (2017). Large-signal model of DC micro-grid systems feeding a constant power load. In: 2017 International Electrical Engineering Congress (iEECON), Pattaya, Thailand, p. 21-24. <https://doi.org/10.1109/IEECON.2017.8075724>
- Pakdeeto, J., Areerak, K., Bozhko, S., and Areerak, K. (2021). Stabilization of DC microgrid systems using the loop-cancellation technique. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 9(3):2652-2663. <https://doi.org/10.1109/JESTPE.2021.3053349>
- Phosung, R., Areerak, K., Sopapirm, T., and Areerak, K. (2021). Design and optimization of instability mitigation for AC-DC feeder systems with constant power loads using artificial intelligence techniques. *IEEE Transactions on Power Electronics*, 37(5):5385-5397. <https://doi.org/10.1109/TPEL.2021.3136354>
- Rivetta, C., Williamson, G.A., and Emadi, A. (2005). Constant power loads and negative impedance instability in sea and undersea vehicles: statement of the problem and comprehensive large-signal solution. In: *IEEE Electric Ship Technologies Symposium*, Philadelphia, PA, USA, p. 313-320. <https://doi.org/10.1109/ESTS.2005.1524694>