Enhancement of Power System Operation for Taipei MRT Network

Hui-Jen Chuang, Chao-Shun Chen, Liang-Jane Fan, and Chin-Yin Ho

Abstract—This paper is to investigate the power system operation strategy for an electrified mass rapid transit (MRT) network to enhance the loading factors of main transformers. The train motion equation has been applied to find the mechanical power demand profiles of the train set according to various operation modes by considering operation resistance. The DC load flow analysis is executed to derive the electric power loading of each traction substation and the AC load flow analysis is then performed to solve the dynamic loading behavior of main transformers for each time snapshot. To improve the loading factors of main transformers, the proper strategy of unit commitment and load transfer by switching operation are determined for the MRT operation during the peak and off peak periods. The Taipei MRT network is selected for computer simulation to demonstrate the effectiveness of the proposed methodology. It is found that the loading factors of main transformers can be improved dramatically and the load balance among the transformers can be obtained by the proposed methodology.

Index Terms—Mass Rapid Transit (MRT), AC and DC Load Flow Analysis, Load Transfer

I. INTRODUCTION

The electrified MRT system provides important public transportation capability for metropolitan area because it can handle very heavy ridership without causing air pollution problem. For the heavy rail MRT system in the large city such as Hong Kong, Tokyo, etc., the operation headway has been reduced to be less than 2 minutes and the hourly ridership of one direction for each MRT line has reached more than 90,000 passengers. To maintain the high efficiency and service level of MRT systems, the reliability of electric power supply becomes one of the very critical issues. It is a conventional way to design the capacity of main transformers in the bulk power substations to cover the peak loading of target year with full redundancy. This implies that the main transformers are operated with 50% loading factor for only the short peak period of the target year. The operation efficiency of MRT power systems is always deteriorated because the main transformers are operated with very light loading level for most of the time since the commission of the substations due to severe over design problem of transformer capacity during the planning stage. Because the electricity charge may contribute rather high percentage of the total operation cost for a heavy rail MRT system, it is expected that significant energy conservation can be obtained by designing the optimal strategy for the power system operation.

To enhance the transformer loading factors and maintain the power system reliability with proper capacity reserve, the load transfer among main transformers of an MRT power system is proposed in this paper. The Taipei MRT network which consists of six routes has been selected for power flow analysis to derive the power demand of main transformers during peak and off peak operation period. The operation timetable of MRT network is used to define the train location, speed and acceleration for each time snapshot. The mechanical power demand of the train operation to meet the schedule timetable is solved by considering the traction effort for the train acceleration and various types of operation resistance. In each train set, 16 units of 250hp three-phase induction motors are used to provide the propulsion power. By considering the efficiency of energy conversion for the inverter, gears, and motors, the input electric power of the train set is then derived. Each train set is treated as a load bus in the load flow analysis and the number of train sets to be put into operation for each MRT line is determined by the scheduled timetable. The impedance matrix of dc network is defined by the actual locations of all train sets. To achieve better performance and control for the train operation, the train borne variable voltage and variable frequency (VVVF) inverter is applied to convert the dc power source to ac power supply with frequency adjusted by the speed code from the control center. The voltage magnitude of the ac power supply is controlled adaptively by the traction effort or torque to drive the train set with the specified passenger loading. The power demand of the traction substations and the main transformers can be solved by load flow analysis [1-3].

To derive the operation strategy of Taipei MRT power system for the target year of 2021, the power consumption of all main transformers is simulated by the forecast ridership with 2-minute headway. The binary integer programming is applied to derive the proper switching operation for load transfer among main transformers. The transformer copper loss and core loss for the MRT power system with feeder reconfiguration [4-6] is solved to find the benefit resulted from the proposed switching operation.

II. DESCRIPTION OF MRT POWER SYSTEMS AND TRAIN OPERATION

To provide the electricity service for the MRT network, the bulk power substations (BSS) have been installed as...
shown in Fig.1 to step down the voltage level of 161 kV from Taipower network to 22 kV for the traction and station power demand. In each BSS, the secondary sides of two traction transformers (TTR) with 25 MVA capacity each are tied together to serve the traction substations (TSS) along the main lines. The ring main units (RMU) are used so that the power supply to the TSS can be switched over to the neighboring BSS when the outage of the service BSS occurs. In the TSS, the 22 kV voltage is stepped down to 589V and 24 pulse rectifiers are used to convert the ac power supply to 750V dc power source for the train sets [7,8]. The dc output voltage of TSS is connected to the third rail by cable and will be collected by the train set when it moves along the main lines.

A. Train Control

On the train set, the dc voltage is converted to three-phase ac power source by VVVF for the control of induction motors to generate the required traction effort at the specified speed. Fig.2 shows the control block diagram for the operation of VVVF inverter [9] is Taipei rolling stock. The speed code, which is picked up by the train borne antenna from the running rail, is used to calculate the corresponding acceleration and the required traction effort, Treq for the train set propulsion. By comparing the Treq to the actual torque output (Tout) generated based on the voltage, current and motor speed, the requested voltage and frequency are determined to perform the waveform synthesis to output the firing signal for the inverter. To achieve better operation performance of the train sets, the operation modes of pulse width modulation (PWM), quasi-six step and six step are applied for the VVVF inverter with the frequency ranges of 0<f<35Hz, 35 ≤ f<67Hz and f ≥ 67Hz respectively. Fig.3 shows the output traction effort of the induction motors at different speeds [9]. When a train set starts from the station in Region I, the constant torque is applied for the speed up to 42km/h. In this region, the PWM is first used for the first portion and the quasi-six-step is used for the second portion of the speed range. The applied voltage level is increased linearly with the train speed to keep the air gap flux constant. The application of quasi-six-step is to achieve the smooth transition during the train acceleration stage. When the train speed reaches 42km/h, the six-step is applied for the operation of constant power in region II and constant slip frequency in region III. For these operation regions, the reduced flux is used to provide constant voltage to the induction motors. In region II, the traction effort is reduced linearly with the increase of the train speed. In region III, the traction torque is reduced with the square of the induction motor slip.

Because the distance between two stations is always very short for MRT lines, the train set has to be operated with high acceleration when it leaves the train station and high deceleration is applied when it approaches the next station. A lot of energy will be wasted with the frequent by train braking and large air conditioner loading will be required for the cooling of train stations. To solve the problem, the electric braking is applied to restore the kinetic energy when the train sets decelerate for stop. The energy regeneration is obtained by controlling the frequency of the inverter output voltage to be less than the rotor speed so that the propulsion induction motors become induction generators. With the negative slip, the train kinetic energy is converted to the regeneration power, which will be fed back to the dc circuit to provide the power supply for another train set with acceleration operation mode.

B. Power Consumption of MRT Train Sets

When the train set starts from the station, the operation modes of constant torque and constant power are applied for the train acceleration until the specified speed has been reached. During this operation stage, the induction motors are driven by the VVVF inverter to generate the propulsion torque. The power demand of the train set is varied from time to time according to the operating speed and traction effort required. The coasting operation mode is then applied by disabling the
frequency and voltage request of the VVVF controller so that the input power to the propulsion motors is disconnected. By this way, significant energy conservation can be obtained although the traveling time to complete the journey will be a little longer. When the train approaches the next station for stop, the braking operation mode is used to recover the train kinetic energy by electric regeneration. For each operation mode, the power consumption or regeneration of the train set can be analyzed by the motion equation according to the passenger loading factor, operation mode and various types of operation resistance of the train set. Equation (1) illustrates the traction effort for the train motion [10].

\[ F_A = M \cdot a + T_{RR} + T_{RA} + G + C \]  

(1)

\( M \) is the mass of the train set and \( a \) is the train acceleration or deceleration. \( T_{RR} \), \( T_{RA} \), \( G \), and \( C \) are the motion resistance of train rolling, aerodynamic, route gradient and curvature.

The train speed is solved by Euler’s method as equation (2).

\[ V_{n+1} = V_n + a_n \cdot dt \]  

(2)

The mechanical power output of the traction motors is solved as equation (3)

\[ P_{out} = F_A \cdot V \]  

(3)

Fig.4 shows the mechanical power consumption of a train set to fulfill the trip from the first station to the third station for Taipei Tamshui line. The actual loading factor is 76% and the station dwelling time is 20 seconds. The power consumption is increased with the speed because the operation mode of constant acceleration has been applied when the train set leaves the station. The constant power is used to achieve further acceleration until the predefined coasting speed has been reached. Only the auxiliary power for train air conditioners etc. is required during the coasting period. The power consumption becomes negative when the train set approaches the next station with the electric braking mode by operating the induction motors with induction generation. It is found that larger power has been regenerated than the peak power demand during the acceleration stage because the train speed is much higher when the electric braking is applied. The efficiency of power recovered by braking regeneration depends on the operation headway. The shorter headway will provide better opportunity for the regenerated power to be consumed by the other accelerating train set in the same service zone of the traction substation. The power restoration will be deteriorated when the power dissipation is applied to reduce the voltage rise when the MRT system is operated with longer headway.

III. LOAD FLOW ANALYSIS OF MRT POWER SYSTEMS

After solving the mechanical power consumption and the corresponding location of the train set for each time snapshot during the journey from the first station to the last station, the data array \((p, x, t)\) is solved by train motion equation. The power consumption \(p\) will be stored as the power demand of the load bus. The location \(x\) will be used to modify the impedance matrix by the resistance of the third rail and running rail. The power loading of each traction substation TSS is simulated with all the train sets on the main line by the MRT operation timetable. The AC load flow analysis is then executed to find the power demand of all BSS and the system voltage drop for each time snapshot.

![Fig.4 Power demand and speed profiles of a train set with regeneration braking by computer simulation.](image)

![Fig.5 Power consumption of Tamshui line during peak operation by computer simulation.](image)

![Fig.6 Power consumption of Tamshui Line during off peak operation with 10-minute headway.](image)

Fig.5 shows the power consumption of Tamshui line by computer simulation with 4 second time snapshot for the time period from 8:40 to 8:46 AM during the peak operation with 6-minute headway. The electric regeneration braking is applied for the train sets to restore the energy consumption. There is dramatically variation of the system power consumption because of the dynamic process of the train set operation. When the overall system power consumption is small, it represents that most of the power demand of the accelerating train sets is supplied by the braking regeneration of the decelerating train sets. The average power consumption of all BSS during the peak period is 9128 kW.

![Fig.5 Power consumption of Tamshui line during peak operation by computer simulation.](image)

Fig.6 shows the power consumption of Tamshui Line during off peak operation with 10-minute headway. Because fewer train sets are operated for the off peak operation, the average power consumption of the MRT system is 5684 kW only, which is much less as compared to the peak operation.
Fig. 6 Power consumption of Tamshui line during off peak operation by computer simulation.

To solve the load transfer among the main transformers of Taipei MRT lines for the target year, the power consumption of each BSS has been derived. For the computer simulation, the train sets are operated with 100% loading factor and the headway is 2 minutes during peak period and the loading factor is 40% and the headway is 6 minutes for the off peak operation. The loading factor of a train set for Taipei MRT system is defined as 100% when it carries 2000 passengers. Fig. 7 shows the voltage variation of 22 kV buses. The largest voltage drop is found to be 4.26%, which is within the 5% constraint.

Fig. 7 The largest voltage drop of all 22KV buses for the peak operation.

Fig. 8 shows the power demand of Tamshui Line for the target year over 10 minutes interval both peak and off peak operation and Table 1 shows the power demand with the corresponding loading factors of all BSS. The total power demands of all BSS to serve the whole Taipei MRT network are solved to be 255.5 MVA and 100.5 MVA during the peak and off peak operation respectively.

IV. LOAD TRANSFER OF MAIN TRANSFORMERS

To improve the operation efficiency of MRT power systems, the unit commitment of main transformers has to be performed to provide sufficient capacity to meet the loading demand and maintain service reliability for system peak and off peak operation respectively. After that, the load transfer among the main transformers has to be executed to achieve the loading balance and minimization of transformer losses. Fig. 9 illustrates the design of main transformer operation for an MRT network. To demonstrate the effectiveness of the proposed methodology, the power system of Taipei MRT network assumed in Fig. 10 is selected for computer simulation. 12 bulk substations (BSS) have been installed to import the power from utility company for the 56 traction substations and stations of all MRT lines. The ring main units (RMU) are applied to provide the open/close control of line switches for the load transfer between two BSS. In this paper, the power network to serve the MRT system is reconfigured by identifying the proper switch operations so that the total system power demand can be reallocated among the main transformers. Notation (X,Y) is often used to represent the operation of opening switch X and closing switching Y. For any switching operation to be performed the radial configuration of power system has to be maintained to prevent the circulation current of main transformers.

Fig. 9 Unit commitment and load transfer of MRT main transformer
A. Binary Integer Programming (BIP) [11]

The load transfer of main transformers by switching operation is a decision making process. During the solution process, the integer variables with values 1 or 0 are used to represent the switching action to be taken or prohibited respectively. The branch and bound technique is applied in this study to find the optimal switching combination in a very effective way without requiring the exhaustive search [11].

The objective function of BIP is defined as

\[ Z = \max \Delta C_{ij} X_{ij} \]  

subject to

\[ \sum_{j=1}^{m} X_{ij} = 1, \quad \text{for} \quad i \in (H) \]  

\[ \sum_{i=1}^{n} X_{ij} \leq 1, \quad \text{for} \quad j \in (L) \]  

\[ \Delta VD \leq 5\% \]  

where \((H)\) is the set formed by the main transformers with heavy loading and \((L)\) is the set formed by the main transformers with light loading. \(C_{ij}\) represents the equivalent cost defined by the summation of loading factor square of main transformer \(i\) and \(j\). To simplify the load transfer problem, equation (5) implies that one and only one lightly loaded transformer has to be selected to accepted partial loading of over loaded transformer \(i\). Also, equation (6) means that each lightly loaded transformer can at most be considered to solve the transformer over loading problem.

\[ C_{ij} = \frac{P_i^2 + Q_i^2}{S_i^2} + \frac{P_j^2 + Q_j^2}{S_j^2} \]  

\(\Delta C_{ij}\) is the cost reduction by the load transfer from main transformer \(i\) and to main transformer \(j\) [5]. Equation (7) implies that the maximum voltage drop of the resultant system after switching operation must be less than 5%.

B. Switching Strategy for System Peak Operation

For the target year, the average power demand of bulk power substation (BSS) in Taipei MRT network has been solved by load flow analysis as shown in Table 1. The power loading of the BSS varies from each other dramatically during the peak operation period. Substation TJ is the most heavily loaded with 26.6 MVA and substation HY is the most lightly loaded with 10.94 MVA. With such a large difference of the transformer loading level, the transformer loss reduction can be obtained by proper switching operation. After performing the binary integer programming, the following switching operation \((3,118), (23,105), (54,113), (59,111), (72,131), (76,104)\) in Fig.10 are proposed for the peak operation. For instance, the switching operation \((3,118)\) will perform the load transfer from BSS TJ to BSS LC. By the same way, the switching operation \((23,105)\) will achieve the load transfer from BSS HJ to BSS SJ. Table 2 lists the new transformer loading and Fig.11 shows the transformers loss reduction after switching operation. It is found that the loading balance among the main transformers has been improved. By executing load flow analysis, it is found that the transformer loss has also been reduced from 735 kW to 718 kW and the largest voltage drop for the 22 kV bus is 3.9%. According to the load transfer among main transformers of Taipei MRT network, the load balance of transformers has been obtained by considering the passenger ridership of all MRT lines. Besides, the transformer operation efficiency and system voltage profile have been improved by the proposed switching
operation.

![Power loss of all main transformers for the peak operation of Taipei MRT network.](image1)

Table 1: Average loading level and loading factors of Taipei MRT main transformers. (original configuration)

<table>
<thead>
<tr>
<th>BSS</th>
<th>Peak operation (MVA)</th>
<th>LF*</th>
<th>Off peak operation (MVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TJ</td>
<td>26.6</td>
<td>0.532</td>
<td>9.37</td>
</tr>
<tr>
<td>HUJ</td>
<td>18.92</td>
<td>0.378</td>
<td>5.83</td>
</tr>
<tr>
<td>HJ</td>
<td>22.45</td>
<td>0.449</td>
<td>8.74</td>
</tr>
<tr>
<td>YJ</td>
<td>24.93</td>
<td>0.499</td>
<td>16.07</td>
</tr>
<tr>
<td>SFJ</td>
<td>24.71</td>
<td>0.494</td>
<td>11.71</td>
</tr>
<tr>
<td>TUJ</td>
<td>22.64</td>
<td>0.453</td>
<td>10.77</td>
</tr>
<tr>
<td>SC</td>
<td>15.75</td>
<td>0.315</td>
<td>10.39</td>
</tr>
<tr>
<td>MT</td>
<td>16.25</td>
<td>0.325</td>
<td>6.01</td>
</tr>
<tr>
<td>SJ</td>
<td>14.61</td>
<td>0.292</td>
<td>5.44</td>
</tr>
<tr>
<td>LC</td>
<td>11.48</td>
<td>0.230</td>
<td>6.26</td>
</tr>
<tr>
<td>SS</td>
<td>16.25</td>
<td>0.325</td>
<td>5.83</td>
</tr>
<tr>
<td>HY</td>
<td>10.94</td>
<td>0.219</td>
<td>4.12</td>
</tr>
<tr>
<td>TOTAL</td>
<td>255.53</td>
<td>100.54</td>
<td></td>
</tr>
</tbody>
</table>

LF*: loading factor (Loading/50)

![Power loss of all main transformers for the off peak operation of Taipei MRT network.](image2)

Table 2: Average loading level and loading factors of Taipei MRT main transformers. (after load transfer)

<table>
<thead>
<tr>
<th>BSS</th>
<th>Peak operation (MVA)</th>
<th>LF*</th>
<th>Off peak operation (MVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TJ</td>
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<td>7.1</td>
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<tr>
<td>HUJ</td>
<td>18.92</td>
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</tr>
<tr>
<td>HJ</td>
<td>22.45</td>
<td>0.449</td>
<td>8.74</td>
</tr>
<tr>
<td>YJ</td>
<td>24.93</td>
<td>0.499</td>
<td>11.7</td>
</tr>
<tr>
<td>SFJ</td>
<td>24.71</td>
<td>0.494</td>
<td>8.93</td>
</tr>
<tr>
<td>TUJ</td>
<td>22.64</td>
<td>0.453</td>
<td>10.77</td>
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<tr>
<td>SC</td>
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<td>8.73</td>
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<tr>
<td>MT</td>
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<td>0.325</td>
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<tr>
<td>LC</td>
<td>11.48</td>
<td>0.230</td>
<td>6.26</td>
</tr>
<tr>
<td>SS</td>
<td>16.25</td>
<td>0.325</td>
<td>10.38</td>
</tr>
<tr>
<td>HY</td>
<td>10.94</td>
<td>0.219</td>
<td>6.9</td>
</tr>
<tr>
<td>TOTAL</td>
<td>255.53</td>
<td>100.54</td>
<td></td>
</tr>
</tbody>
</table>

C. Switching Strategy for System Off Peak Operation

The ridership of MRT lines for the off peak operation is much smaller than that for the peak operation. By executing the load flow analysis, it is found that all of the main transformers are very lightly loaded and the average loading factor is only 16% as shown in Table 1. To enhance the system operation efficiency and provide sufficient capacity reserve for system reliability, it is suggested that only one main transformer unit in each BSS is required to be committed for the off peak operation and the other unit is shutdown for backup. By performing the binary integer programming, the switching operation (3,137), (52,113), (59,111), (33,103) for the off peak operation are proposed. By executing (3,137), partial loading of BSS TJ will be transferred to BSS HUJ. By executing these four switching operations, the main transformers are more evenly loaded. With half of the main transformer units shutdown for backup during the off peak operation and execution of the above switching operations, the transformer loading factors have been improved significantly and the transformer loss has been reduced from 553 kW to 342 kW as illustrated in Fig.12.

V. CONCLUSION

In this paper, the dynamic load behavior of an electrified MRT train set has been investigated by considering different operation modes of train propulsion systems between the stations. The power consumption of the train set for each time snapshot has been derived based on the passenger ridership and the time period required to complete the journey from the first station to the last station. The power demand of the traction substations along the main lines is then solved by DC load flow analysis with the train sets committed on the main lines according to the schedule timetable for the peak and off peak operation. The AC load flow analysis is then performed to calculate the loading level of main transformers. To enhance the power system operation efficiency of MRT networks, the load transfer among main transformers by switching operation has been proposed. The load balance of main transformer is obtained by the operation of ring main unit so that the partial loading of heavily loaded transformer can be transferred to the lightly loaded one. The cost function of switching operation is defined by the transformer loading and the binary integer programming has been applied to derive the optimal switching operation. To demonstrate the effectiveness of the proposed methodology, the Taipei MRT network with 12 bulk power substations and 56 traction substations to serve 6 main lines has been selected for computer simulation. The peak and off peak power demand of all BSS has been solved for the target year. It is found that loading unbalance among the main transformers is very
serious during the peak period. By performing load transfer with six optimal switching operations, the load balance of main transformer is derived among the main transformers. For the off peak operation, it is suggested that only half of the transformer units are required to be committed to meet the system load demand and system reliability. By binary integer programming, very significant loss reduction has been obtained by executing four switching operations. It is concluded that the operation efficiency of an MRT power system can be improved by optimal switching operation and unit commitment of main transformer on daily basis according to the loading level of whole MRT network. Further work on measurement to verify the prediction of the new switching scheme should be carried out.

VI. REFERENCES


VII. BIOGRAPHIES

H. J. Chuang received the B.S. and M.S. degree in Electrical Engineering from National Taiwan University of Science and Technology in 1990 and 1992 respectively, and Ph. D. degree in Electrical Engineering from National Sun Yat-Sen University in 2002. He is presently an Associate Professor at Kao Yuan University, Lu Chu, Taiwan. His research interest is in the area of load flow and power system analysis of mass rapid system.

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