Voltage Stability Assessment of Electrical Railway Network and Proposing the Way to Reduce the Risk of Voltage Instability

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Abstract
The ability of power system to maintain the acceptable range of voltage which is known as voltage stability, may be lost by increasing the real and reactive power consumptions. Voltage instability has been one of the major concerns in electrical railway system operation, since the demand for this transportation system has increased. By increasing the passenger demand, the operational plan should response and as the result the headway time should decrease. This results an increase in the power consumption of network as well as probability of voltage instability. This paper evaluates the risk of voltage instability by presenting the voltage stability index and considering the probabilities of system. To achieve this, the system is simulated by BBA Traction Simulator Program, which is designed and developed by Alucast Iran Co. R&D team. The 2*25 kv AC autotransformer electrical railway network of Sadeghieh to Hashtgerd, Tehran is utilized as a test system to validate the applicability and capability of presented method.

Keywords: Voltage stability, Electrical railway, Risk of instability, BBA Traction Simulator.

Introduction

Voltage instability is a problem of power system which is possible to occur in heavily loaded networks. When the load of system increases, the voltage of nodes decreases dramatically and as a result, the voltage collapse with all consequences resulting from it. Recent studies in this field used to define some indices to evaluate power system voltage instability. Ref [1] used to evaluate voltage stability by defining six different types of line voltage stability indices. In that study the voltage stability indices were formulated based on the power transmission concept in a single line. However [2, 3] derived a voltage stability index from the minimum singular value of the power flow Jacobian matrix. This index also was determined that how far the operating point is from the steady state voltage limit or presents the stability margin. Ref [4] used the topology space theory to describe the phenomena of voltage collapse and the bifurcation points were identified from the singularity of the power flow Jacobian matrix. Studying of voltage collapse at the load bus by using the Thevenin equivalent circuit was presented in [5]. In that study a voltage collapse proximity indicator is derived from the ratio between the load impedance and the Thevenin impedance in the equivalent circuit. In [6, 7] the voltage stability was assessed by using artificial neural network. Voltage stability assessment in DC railway system is studied in [7]. Due to sudden and frequent changes in power consumption of railway system, the relation between train traffic operation and the voltage collapse must be carefully studied.
The risk based approach to security assessment for a voltage stability constrained power system was studied in [8]. In [9, 10] the risk based voltage stability was studied and to avoid that risks the emergency load shedding was used. A real time voltage instability identification based on local phasor measurements was presented in [11]. In that study the risk is based on computation of Thevenin equivalent impedance of the classic electrical circuit.
In this paper the voltage stability of AC autotransformer railway system is assessed. To achieve this, risk of voltage instability is defined by using the uncertainties of system. The different scenarios with their probabilities are considered to evaluate risk. To reduce the risk of voltage instability manners and compensation methods are proposed.

Derivation of Voltage Stability

To define the voltage stability index, the load flow equations are considered. The mathematical formulation is derived from a two bus network as shown in Fig. 1.

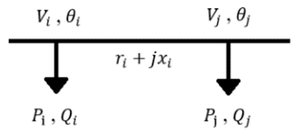

Figure 1. Two bus network diagram

$$|I_i|^2 = \frac{P_i^2 + Q_i^2}{V_i^2} \quad (1)$$

$$|I_j|^2 = \frac{P_j^2 + Q_j^2}{V_j^2} \quad (2)$$

$$P_j = P_i - P_{loss} \quad (3)$$

$$Q_j = Q_i - Q_{loss} \quad (4)$$

$$P_{loss} = \left(\frac{P_j^2 + Q_j^2}{V_j^2}\right) r_i \quad (5)$$

$$Q_{loss} = \left(\frac{P_j^2 + Q_j^2}{V_j^2}\right) x_i \quad (6)$$

From Eq. 1 to Eq.6 the following equation obtains.

$$|I_i|^2 = \frac{\left[P_j + \left(\frac{P_j^2 + Q_j^2}{V_j^2}\right) r_i\right]^2 + \left[Q_j + \left(\frac{P_j^2 + Q_j^2}{V_j^2}\right) x_i\right]^2}{V_i^2} \quad (7)$$

Substituting the left hand side of Eq. 7 with Eq. 1 leads to:

$$V_i^2 = V_j^2 + 2(P_j r_i + Q_j x_i) + \left(\frac{P_j^2 + Q_j^2}{V_j^2}\right)(r_i^2 + x_i^2) \quad (8)$$

$$V_j^4 + V_j^2\left[2(P_j r_i + Q_j x_i) - V_i^2\right] + (P_j^2 + Q_j^2)(r_1^2 + x_1^2) = 0 \quad (10)$$

The equation is quadratic in V_j^2 and it will have real roots if $b^2 - 4ac \geq 0$

Hence from Eq. 9

$$8P_j Q_j r_i x_i - 4V_i^2(P_j r_i + Q_j x_i) + V_i^4 - 4(P_j^2 x_i^2 + Q_j^2 r_i^2) \geq 0 \quad (11)$$

Which can be simplified to:

$$\frac{4\left[V_i^2(P_j r_i + Q_j x_i) + (P_j x_i - Q_j r_i)^2\right]}{V_i^4} \leq 1 \quad (12)$$

Therefore, the voltage stability index is given by:

$$L = \frac{4\left[V_i^2(P_j r_i + Q_j x_i) + (P_j x_i - Q_j r_i)^2\right]}{V_i^4} \quad (13)$$

By considering Eq. 14 and Eq. 15 the Eq. 17 as the voltage stability index (VSI) obtains.

$$V_i V_j cos(\theta_i - \theta_j) - V_j^2 = P_j r_i + Q_j x_i \quad (14)$$

$$V_i V_j sin(\theta_i - \theta_j) = P_j x_i - Q_j r_i \quad (15)$$

$$L_i = \frac{4\left[V_i V_j cos(\theta_i - \theta_j) - V_j^2 cos(\theta_i - \theta_j)\right]}{V_i^2} \quad (16)$$

$$VSI = \sum_{i=1}^{N-1} L_i \quad (17)$$

Where N is the number of nodes.

Risk of Voltage Instability

The uncertainties affecting the operation of power system should be considered in risk of voltage instability assessment. The probabilistic factors, which significantly affect the voltage stability, include those of operating conditions of power system like the outage of substations, topology of network and consumption of system loads. In the current study, it is assumed that the outage of autotransformers in ATPs cause the changes on topology of network by changing the feeding direct of substations. So the effects of the ATPs failure are considered as an uncertainty.

Autotransformers in ATPs may have outage because of failure or overhaul. In that situation, by using the coupling switches the up line and down line are feed by same autotransformer. In heavy loaded systems this can cause the voltage instability. The different scenarios of different ATPs outage by considering the probability of each scenario are taken into the account. The risk of voltage instability is defined as bellow:

$$Risk = \sum_{\omega=1}^{N_\omega} VSI_\omega \times \pi_\omega \qquad (18)$$

Where, VSI_ω and π_ω are the voltage instability index and probability of ωth scenario, respectively. N_ω is the number of considered scenarios. Any method that decrease the value of Eq. 18 can improve the system stability.

Modeling of System

To evaluate the voltage stability and risk, it is important to model system with details and do load flow calculations. Here is a brief explanation of train and network modeling in BBA Traction Simulator software which is designed and developed by Alucast Iran Co. R & D group.

a. Train movement

The fact that the train is moving only further perplexes the load flow calculation and it signifies the difference between a conventional power system and a supply system in railways. The number of trains in system is also vital to the calculation as they may be running at different speeds, drawing or feeding different amount of power and thus posing different effects on the network. Nominal separation among trains is yet another important consideration and it should follow the timetables schedules of the train services. Power drawn from the train depends on the train's speed and operation mode which are in turn determined by the traction equipment characteristics, train weight, aerodynamics, track geometry, train control strategies, rout characteristics and etc. The power demand may thus vary significantly within a very short period of time during an inter-station run.

b. 2*25 kV Electrical Network

The system 2x25 kV is based on the idea of distributing the voltage along the line at higher voltage (50 kV) and feeding the train at 25 kV. For this the substations feed the system at 50 kV and through intermediate autotransformer centers supply power to the rolling stock at 25 kV. To implement the system, the substation will have transformers with secondary at 50 kV with intermediate tap. This tap will be connected to rail and ground performing the functions of neutral in the system. From the two phases, one will be connected to the overhead contact line and the other to the auxiliary feeder also known as negative (voltage is 180º out of phase with respect to the overhead contact line). Thus, between the catenary and the rail there is the required 25 kV. The intermediate autotransformer substations will be connected between the catenary and the negative, with the midpoint connected to rail and ground. Fig. 2 shows the schematic diagram of 2*25 Kv electrical network. Catenary or CW is considered the equivalent of contact and messenger wire which they are paralleled by dropper wires. Also there is protection wire (PW) that is parallel with rail and both of them are carrying the return current of rolling stock system. The Impedance of all wires is influenced by the mutual induction between each other which have been considered in the power flow calculations. It is worth mentioning that calculation of mutual inductance is done by using Carlson method [12] which is considered in BBA Traction Simulator.

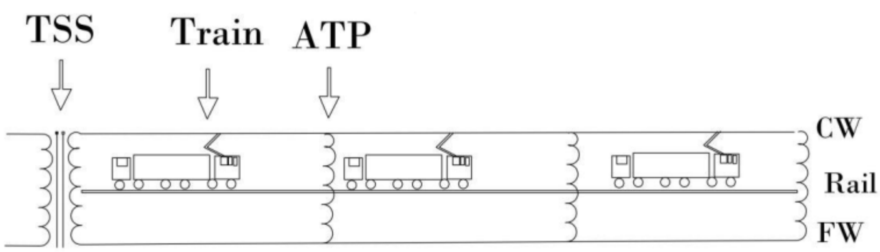

Figure 2. Schematic diagram of 2*25 Kv electrical network

Case Study

To validate the applicability of presented method the 2*25 kv AC electrical railway network of Sadeghieh to Hashtgerd, Tehran is simulated. In table 1 the location of ATPs and TSS are presented. The voltage stability index for considered scenarios which are represented in table 2, are calculated and according to that, the risk of voltage instability obtained. To do this, the power flow calculation was done by BBA Traction Simulator in every considered scenario. In this case the headway time is considered 10 minutes. For this headway time the value of risk of voltage instability obtained 16.534. It is worth mentioning that because the lack of information about historical data of system, the probability of each scenario considered same.

Table 1. Location of ATPs and TSS

Element	substation	Location (km)
ATP	Azadi	0
ATP	Vardavard	15
TSS	Bonyadrang	25
ATP	Golshahr	40.1
ATP	Kordan	52
ATP	Hashtgerd	62.9

Table 2. Considered scenarios and probabilities

Scenario (ω)	**disturbance**	**Probability (π_ω)**
0	All ATPs in line	-
1	Outage of ATP Azadi	0.2
2	Outage of ATP Vardavard	0.2
3	Outage of ATP Golshahr	0.2
4	Outage of ATP Kordan	0.2
5	Outage of ATP Hashtgerd	0.2

Fig. 3 and 4 represent the real power consumption of train in all point of the route from Sadeghieh to Hashtgerd and reverse direction, respectively. According to these diagrams in the stations when train accelerating, the drawing power from the network has its maximum values and it causes a voltage drop on pantograph-earth voltage. If the acceleration of trains occurs simultaneous, it may cause voltage collapse. So to improve the voltage stability of system, it is good idea to deal with time table of trains. The operational plan of system should not allow trains to accelerate simultaneously. To reduce the risk of voltage instability, the operational planning of trains is changed and time table is considered as Fig. 6, while before this changes the time table was considered as Fig. 5. In second time table there are two kinds of trains, usual and express. The express trains don't stop in some passenger stations which can reduce the power demand of system caused by rapid starts of trains.

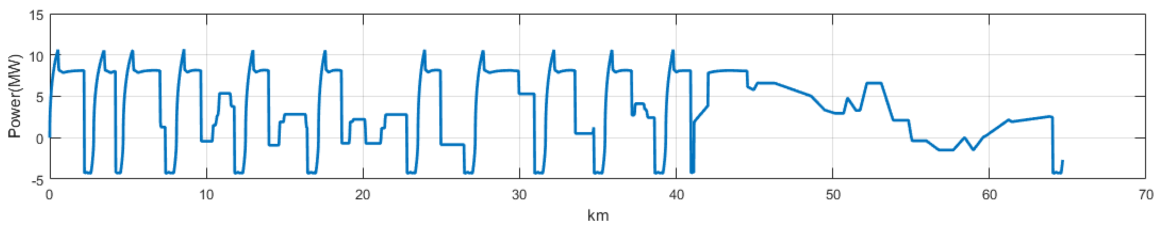

Figure 3. Real power of train in Sadeghieh to Hashtgerd direction.

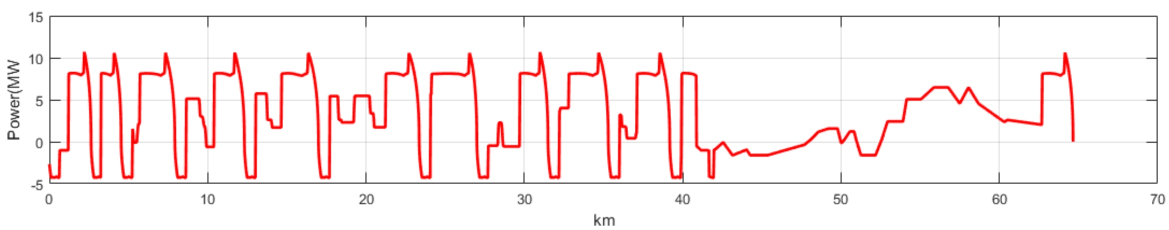

Figure 4. Real power of train in Hashtgerd to Sadeghieh direction.

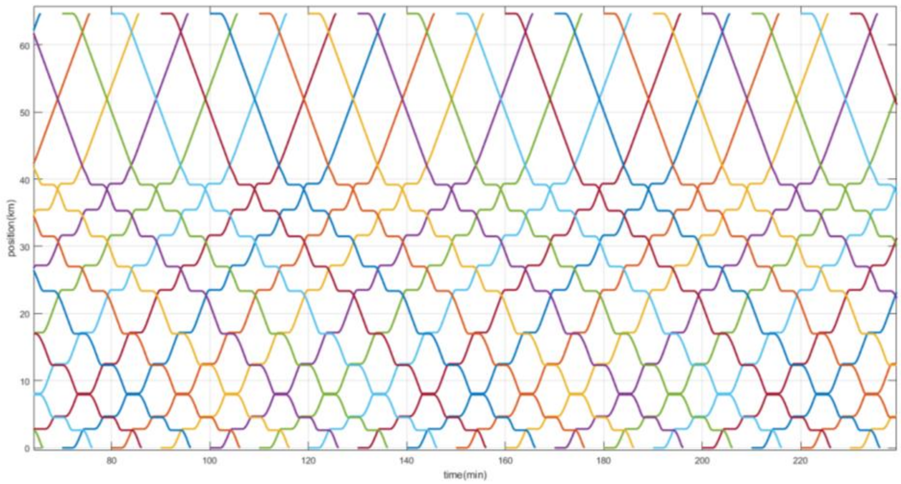

Figure 5. First considered time table diagram of system.

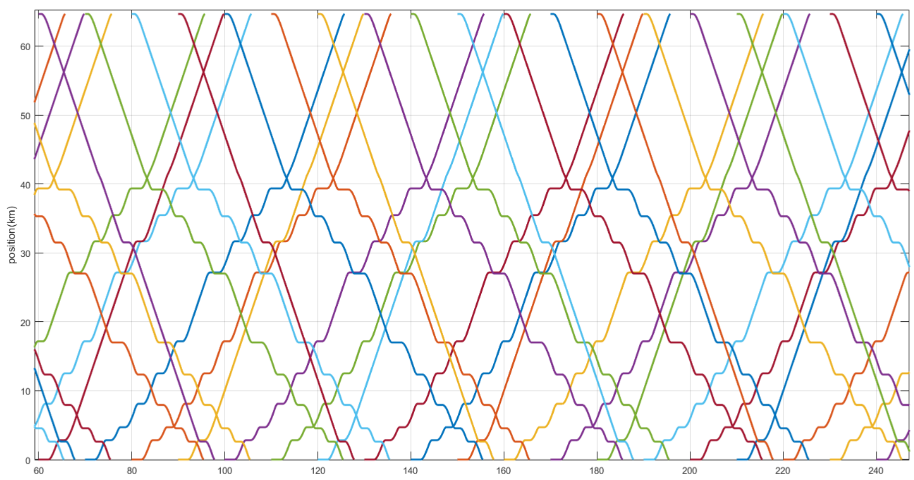

Figure 6. Second considered time table diagram of system.

By considering the same scenarios with same probability for second time table, the risk of voltage instability obtained 9.258 This means that by considering proper operational plan the risk of voltage instability can be decrease as well as headway time. Fig. 7 and Fig. 8 show the voltage profile of system in different scenarios for first time table and second time table, respectively. It is clear that in second time table the voltage profile of system improved. According to these diagrams, the voltage profile of each scenario in case of second time table are stable, as they expected.

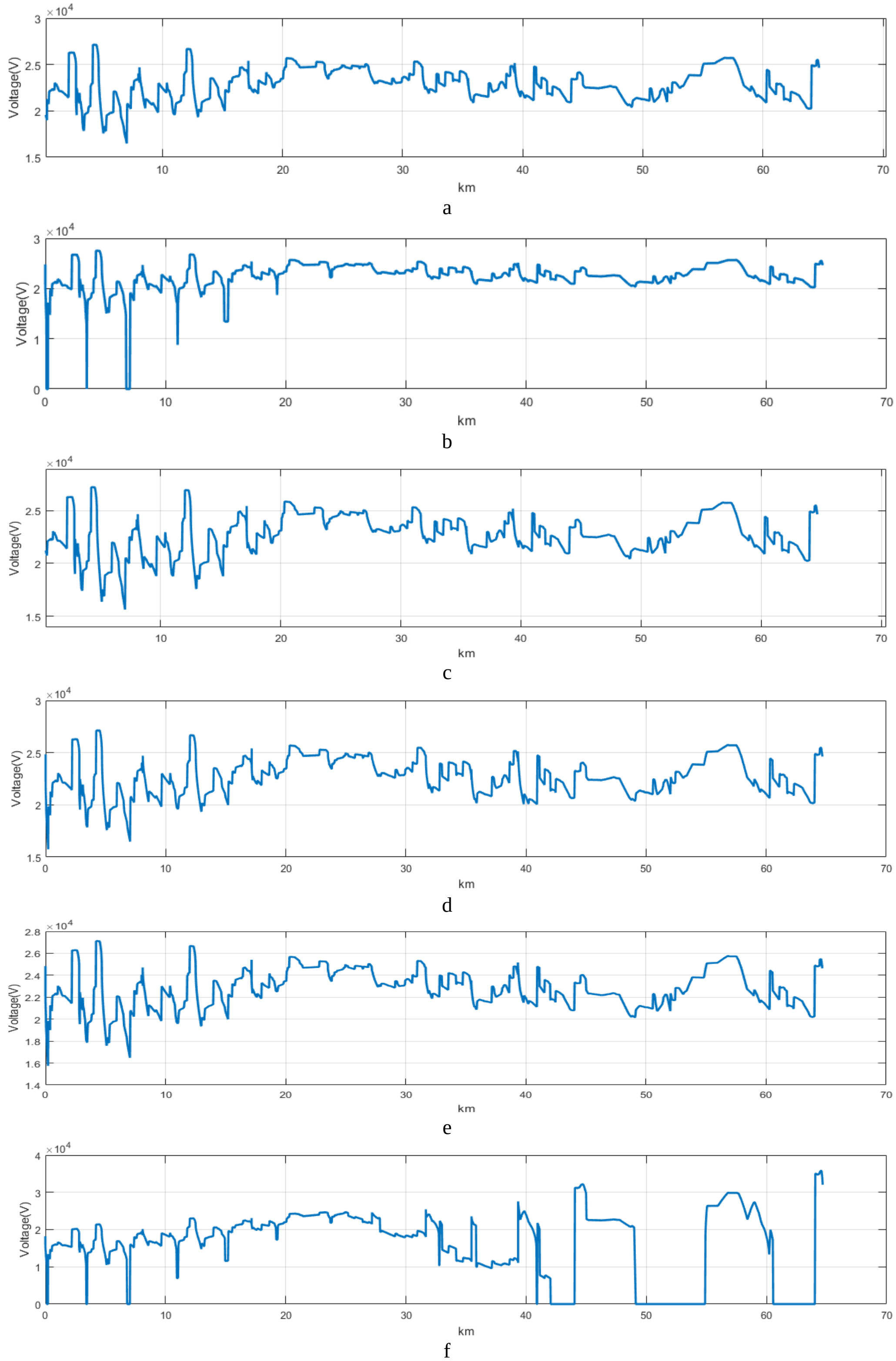

Figure 7. voltage profile of phantograph for first time table diagram for each senarios: **a.** $\omega = 0$, **b.** $\omega = 1$, **c.** $\omega = 2$, **d.** $\omega = 3$, **e.** $\omega = 4$ and **f.** $\omega = 5$, respectively.

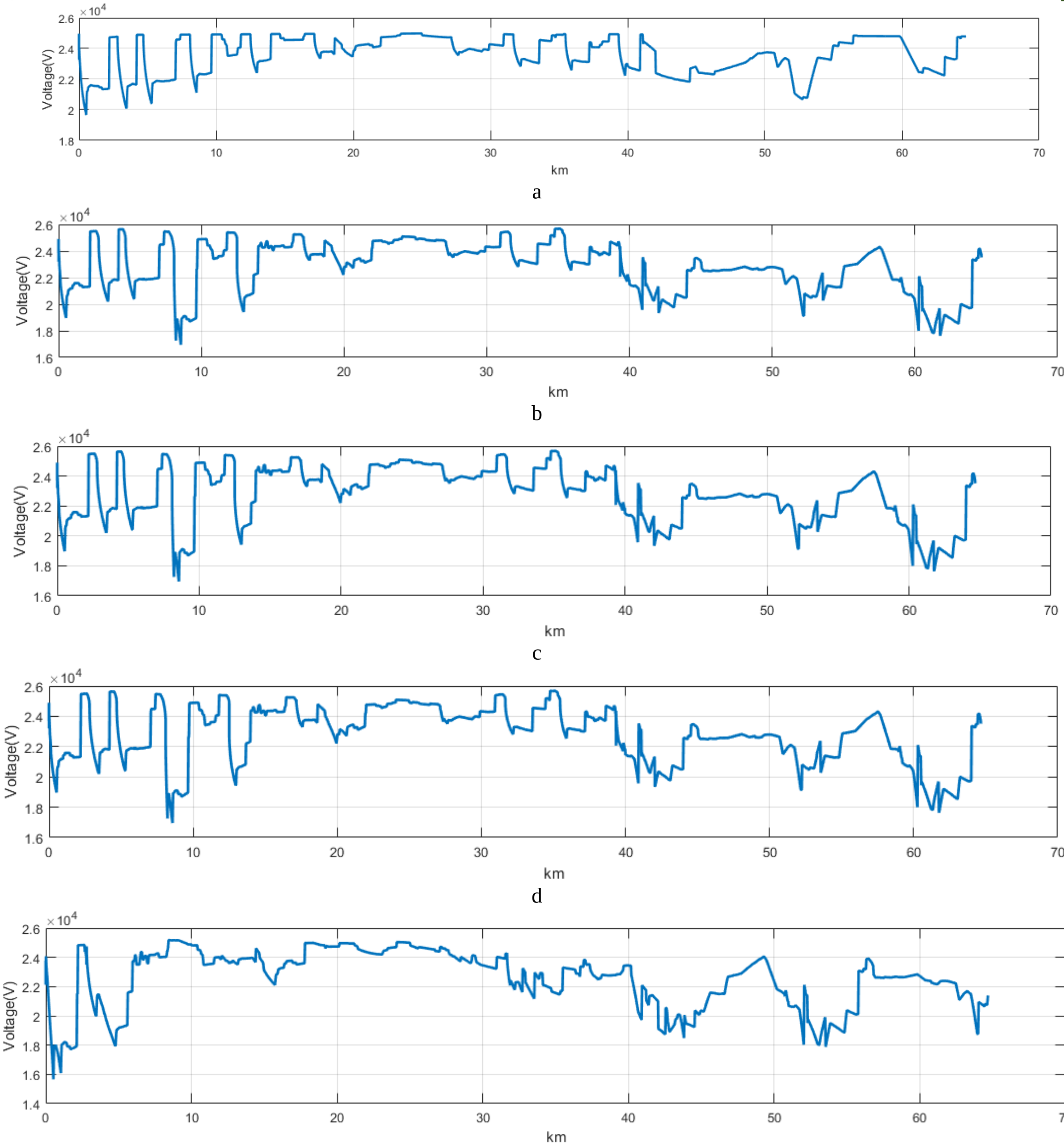

Figure 8. voltage profile of phantograph for second time table diagram for each senarios: **a.** $\omega = 0$, **b.** $\omega = 1$, **c.** $\omega = 2$, **d.** $\omega = 3$, **e.** $\omega = 4$ and **f.** $\omega = 5$, respectively.

Conclusion

In this paper the voltage stability of AC electrical railway system was evaluated and the risk of voltage instability was calculated by considering the system uncertainties. The system was modeled in details and train movement was simulated dynamically. This simulations and the power flow calculation on were done by BBA Traction Simulator which was designed and developed by Alucast Iran Co. R & D group. To show the results of study, the 2*25 kv electrical railway network of Sadeghieh to Hashtgerd, Tehran was simulated. The simulation results show that by arranging the proper time table, the risk of voltage instability can be decreased.

References

[1] H. H. Goh, Q. Chua, S. Lee, B. C. Kok, K. C. Goh, and K. Teo, "Evaluation for voltage stability indices in power system using artificial neural network," *Procedia Engineering,* vol. 118, pp. 1127-1136, 2015.

[2] P.-A. Lof, T. Smed, G. Andersson, and D. Hill, "Fast calculation of a voltage stability index," *IEEE Transactions on Power Systems,* vol. 7, pp. 54-64, 1992.

[3] P.-A. Lof, G. Andersson, and D. Hill, "Voltage stability indices for stressed power systems," *IEEE transactions on power systems,* vol. 8, pp. 326-335, 1993.

[4] J. A. Momoh and Y. Zhang, "Voltage stability estimation," in *Systems, Man and Cybernetics, 1990. Conference Proceedings., IEEE International Conference on*, 1990, pp. 94-97.

[5] A. Chebbo, M. Irving, and M. Sterling, "Voltage collapse proximity indicator: behaviour and implications," in *IEE Proceedings C (Generation, Transmission and Distribution)*, 1992, pp. 241-252.

[6] A. C. Andrade, F. M. Barbosa, J. Fidalgo, and J. R. Ferreira, "Voltage stability assessment using a new FSQV method and artificial neural networks," in *Electrotechnical Conference, 2006. MELECON 2006. IEEE Mediterranean*, 2006, pp. 1003-1006.

[7] O. Rahi, A. K. Yadav, H. Malik, A. Azeem, and B. Kr, "Power system voltage stability assessment through artificial neural network," *Procedia Engineering,* vol. 30, pp. 53-60, 2012.

[8] H. Wan, J. D. McCalley, and V. Vittal, "Risk based voltage security assessment," *IEEE Transactions on Power Systems,* vol. 15, pp. 1247-1254, 2000.

[9] T. Tuan, J. Fandino, N. Hadjsaid, J. Sabonnadiere, and H. Vu, "Emergency load shedding to avoid risks of voltage instability using indicators," *IEEE Transactions on Power Systems,* vol. 9, pp. 341-351, 1994.

[10] M. El-Sadek, G. Mahmoud, M. Dessouky, and W. Rashed, "Optimum load shedding for avoiding steady-state voltage instability," *Electric power systems research,* vol. 50, pp. 119-123, 1999.

[11] S. Corsi and G. N. Taranto, "A real-time voltage instability identification algorithm based on local phasor measurements," *IEEE transactions on power systems,* vol. 23, pp. 1271-1279, 2008.

[12] F. M. Tesche, M. Ianoz, and T. Karlsson, *EMC analysis methods and computational models*: John Wiley & Sons, 1997.