Determination of maximum level of EV penetration with consideration of EV charging load and harmonic currents

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Abstract. In order to accommodate Electric Vehicles (EVs) charging demand which is expected to rise steeply in the coming years due to environmental concerns on global warming, it is important to determine the maximum EV penetration can be allowed without network upgrading and avoid overloading of Medium Voltage (MV) cables and distribution transformers in residential distribution power systems. Previous work on modelling and analysis of relationship between the temperature of MV cables and transformer with EV penetration level failed to consider the contribution of harmonic distortion in the demand. In this paper, a methodology is proposed to model the EV penetration and their effects on operational temperature of MV cables and transformers, with charging scenarios and harmonic currents taken into consideration. The method is simulated in a typical urban residential distribution system. The results show that EV penetration above 27.25 % with 6.6 kW EV chargers charging in uncontrolled domestic scenario will lead to 10 kV 400 mm\(^2\) three core cable overloading in the simulation with harmonic current taken into consideration. The result is 30.74 % if harmonic currents are ignored. The maximum allowable EV penetration of 35/10 kV 16 MVA and 10 kV 1250 kVA transformer is 50.22% and 26.19% respectively. If EVs charge in off-peak time, the cable and transformer can avoid overloading and the charging cost is lower.

1. Introduction
The rapid growth of EV charging demand increases the overload risk of equipment in distribution networks (DNs) which are already heavily loaded in many urban residential areas in countries around the world. Especially in China where most metropolises are of temperate or subtropical monsoon climate, and the peak demand and ambient temperature appear simultaneously in summer because of the high usage of air conditioners. The load demand, temperature increase and thermal aging of cables and transformers caused by EV charging have been modelled by the present authors in literatures [1-3]. However, their earlier work and reported by others [4-5] may have underestimated the impact of EV charging, because of the ignorance of additional AC loss due to the harmonic current caused by AC/DC converters. Consequently, without consideration of harmonic current due to EV charging may lead to cable and transformer overloading. Furthermore, the rated ampacity of cables and capacity of transformer have been determined by traditional model with consideration of future power load...
increases when a DN was designed [6]. On account of 20-40 years designed life, it is essential to allow derating of MV cables and transformers ampcacity caused by the fast emerging non-sinusoidal loads such as EV chargers to be modelled to avoid overloading. This paper aims to model maximum level of EV penetration allowable in a distribution system and analyse its impact on operational temperature of MV cables and transformers with harmonic current taken into consideration.

2. Mathematic models

The capacity of electrical devices such as cables and transformers in distribution system are influenced by the level of load as well as harmonic components. With the increase in harmonic orders, active power loss increases because of skin effect and proximity effect. In order to investigate the impacts on cables and transformers, the load power with harmonic component is defined in Equation 1, in which $P_h$ and $P_f$ is harmonic power per unit, fundamental power per unit, $I_i$ is current of $i$th order, $n$ is the maximum harmonic order.

$$\frac{P_h}{P_f} = \sqrt{\sum_{i=1}^{n} I_i^2}$$

Then, the equations of cables and transformers temperature are deduced from the equations provided by IEC 60287 and IEEE Std C57.110 [7, 8]. Because the magnitude of harmonic currents above 19th due to EV charging is low, their thermal effect on MV cables and transformers is ignored in this paper. The temperature model of a three core cable carrying non-sinusoidal current is presented in Equation 2, in which $\theta_c$ is conductor temperature of cable, $R_{AC}$ is the AC resistance of conductor, $c_n$ is the number of conductors and $\lambda_2$ is loss ratio of armour layer. If the thermal resistances $T_{in}, T_{o}, T_{o2}, T_{a}$ and ambient temperature $\theta_A$ become available via either measurement or calculation, the conductor temperature in Equation 2 can be obtained.

$$\theta_c = \sum_{i=1}^{n} \frac{I_i^2}{T_i} \times R_{AC} (i) (T_i + c_0 T_2 + c_1 (1 + \lambda_2 (i)) (T_i + T_o)) \theta_i$$

At any time instant $t$, the hot-spot temperature $\theta_g$ of transformer consists of three components defined in Equation 3, where $\theta_{in}, \Delta\theta_{TO}$ and $\Delta\theta_g$ are the ambient temperature, then top-oil temperature rise over ambient temperature, and the winding hotspot rise over top-oil temperature, respectively, during the time interval $\Delta t$ in degree Celsius.

$$\theta_g = \theta_{in} + \Delta\theta_{TO} + \Delta\theta_g$$

The top oil temperature rise above ambient temperature $\Delta\theta_{TO}$ with sinusoidal load is defined in Equation 4, in which $\theta_{TO,R}$ is top oil temperature rise at rated load, $\Delta t$ is time interval, $R$ is the ratio of load loss to no-load loss, $\tau_{TO,R}$ is the oil time constant at rated condition in hours, $p$ is an empirically derived exponent to account for effects of change in resistance with change in load.

$$\Delta\theta_{TO}(t) = \left[ \frac{K^2(t+\Delta t) R+1}{R+1} \right]^p - \left[ \frac{K^2(t) R+1}{R+1} \right]^p \times \left[ 1 - \exp \left( \frac{-\Delta t}{\tau_{TO,R}} \right) \right] \left[ \frac{K^2(t+\Delta t) R+1}{R+1} \right]^p$$

Similarly, the hot-spot temperature rise to top oil temperature is defined in Equation 5, in which $\theta_g$ is the hot-spot temperature rise over top-oil temperature at rated load, $\tau_m$ is the winding time constant in hours, $m$ is an empirically derived exponent to account for effects of change in resistance and oil viscosity with change in load.

$$\Delta\theta_{g}(t) = (K^{2m}(t+\Delta t) - K^{2m}(t)) \times \left[ 1 - \exp \left( \frac{-\Delta t}{\tau_m} \right) \right] + K^{2m}(t)$$

The model of transformer is formulated by power loss per unit. The power loss of transformer are defined by Equation 6, in which $P_{LL}$ is the load loss, $P$ is conductor loss portion of the load loss, $F_{HLL}$ is harmonic loss factor for winding eddy current, $P_{EC}$ is the winding eddy-current loss, $F_{HLL-STB}$ is the harmonic loss factor for other stray losses, $P_{OBL}$ is the other stray loss.
The method to calculate $F_{HL}$ and $F_{HL,STR}$ is provided by IEEE std 57.110. If the magnitude and order of harmonic current can be obtained via measurement or simulation, the $P_{LL}$ can be calculated. The load ratio $K(t, n)$ at time instant $t$ in presence of harmonic current is defined in Equation 7. Using the $K(t, n)$ to change the ratio of the load $K(t)$ at time $t$, $\Delta \theta_{TO}$ and $\Delta \theta_g$ in presence of harmonic load can be obtained.

$$K(t, n) = \frac{P_{LL}(t, n)}{P_{LL,t}} \quad (0 \leq t \leq 24)$$

The maximum level of EV penetration allowable in residential distribution network is determined by cable conductor temperature, hot-spot temperature, hot-spot temperature rise and top oil temperature of transformers.

3. Simulations

A generic urban distribution network which is a representative of urban residential distribution network in China is presented in Fig.1. The system consists of a 500 MVA 35 kV three phase power source, a 10 kV substation, a 35/10 kV 16 MVA transformer (T1) and seven 10/0.4 kV YY0 1250 kVA transformers (T2) and three 10 kV outgoing feeders (F1, F2 and F3). Three phase of a 10 kV cable is consisted of F1, F2 and F3. The power frequency is 50 Hz and the power factor of residential load is set at 0.9. The load ratio of residential load to the rated load of 10 kV 400 mm$^2$ is 0.7, the maximum phase current r.m.s value of 10 kV cable in presence of residential load is 372.24 A. The EV charging load changes with EV penetration. We assume that the three phase cables and transformers are balanced. The total number of vehicles in the studied region is 1246 cars and the EV penetration is set vary from 0 to 70 %. A program is developed in MATLAB based on the methodology presented in this paper. The following data are used in the simulation. The EV can be fully charged in 4 hours at most with a charging power 6.6 kW. The hourly ambient temperature and residential load ratio of a typical summer day is given in Table A1 in the appendices of the paper. Harmonic current of a single phase rectifier and thermal characteristics of cable and transformer are presented in Table A2 and A3 in appendices. In Wuhan, China, most workers start work at 9:00 and go home at 17:00. It is assumed that all the EV users go home after work in this paper, to allow the worst scenario (scenario 1: uncontrolled domestic charging) to be considered. Furthermore, accounting for the average commuting time of EV in Wuhan of 47 minutes, all the EV users are expected to begin their recharge cycles every work day at nearly the same time (at 18:00). The time-of-use electricity rate structure is a typical tariff adopted by electric power company to encourage EV users to charge during the off-peak time. In uncontrolled domestic off-peak charging scenario (scenario 2), it is assumed that all the EV users charge during off-peak time. For instance, in Wuhan, the peak load time is 7:00 to 21:59 while off-peak load time is 22:00 to 6:59 in the next day. In this scenario, the EV owners would charge during the off-peak time and the battery of EVs should be fully charged at the end of off-peak load time.

$$P_{LL} = P + F_{HL} \times P_{ac} + F_{HL,STR} \times P_{ac}$$

(6)
Using Equation 1-7 with values taken from Table A1-A3 the results of allowable maximum EV penetration shown in Table 1 in the simulated system can be obtained. The results in Table 1 show that, with the given condition of cable conductor temperature, the maximum EV penetration decreases by 3.49% if harmonic currents due to EVs charging are taken into consideration. The deciding factor of the transformers are hot-spot temperature in the simulation. Due to limitation in the hot-spot temperature of T1 and T2, the maximum EV penetration will decrease by 5.48% and 2.90% respectively if harmonic currents are taken into consideration.

**Table 1 Allowable maximum EV penetration in simulation confined by permissible temperature**

| With harmonic current | Cable | T1 | T2 |
|-----------------------|-------|----|----|
|                       | Yes   | No | Yes | No | Yes | No |
| θc                    | 27.25 % | 30.74 % | – | – | – | – |
| θg                    | – | – | 50.22 % | 55.70 % | 26.19 % | 29.05 % |
| ΔθTO                  | – | – | 51.46 % | 57.09 % | 27.64 % | 30.65 % |
| Δθg                   | – | – | 55.42 % | 61.48 % | 30.32 % | 33.64 % |
| All conditions        | 27.25 % | 30.74 % | 50.22 % | 55.70 % | 26.19 % | 29.05 % |

The results of hourly temperature in typical scenarios are presented in Fig.2. In uncontrolled domestic charging scenario, the results in Fig.2 (a1-a4) show that, the peak of the conductor temperature of cable, θg, ΔθTO, Δθg appears around 19:00. During the charging time commencing from 18:00 to 22:00, the aforementioned temperatures increase significantly. In off-peak uncontrolled domestic charging scenario, the results in Fig.2 (b1-b4) show that, the peak of the conductor temperature of cable, θg, ΔθTO, Δθg appears also around 19:00, whilst the charging load peak is around 22:00 to 2:00 of the next day. By analysing the results of Fig.2, it can be concluded that cables and transformers can avoid overloading under 30% EV penetration in off-peak uncontrolled domestic charging scenario while the charging cost is lower than uncontrolled domestic charging scenario because of time of use electric price.

**Fig.2** Cable and Transformer temperature in summer in typical charging scenarios (Scenario \(x=1 \text{ or } 2\)): \(a_x\) cable conductor temperature; \(b_x\), hot-spot temperature of 10/0.4 kV transformer; \(c_x\), top oil temperature of 10/0.4 kV transformer; \(d_x\), hot-spot temperature rise of 10/0.4 kV transformer

4. Conclusions

An analytical model is presented to evaluate maximum EV penetration level in a residential distribution system and EV charging impacts on cable and transformer temperature with harmonic current taken into consideration in this paper. Through simulations and analysis, the paper comes into the following conclusions. The capacity of distribution system will decrease due to EVs charging which can be exacerbated when considering the presence of harmonic current. The results of the simulation show that 27.25 % penetration of 6.6 kW EV chargers charging in uncontrolled domestic...
charging scenario will lead to 10 kV 400 mm² three core cable overloading with harmonic current taken into consideration. The result is 30.74% if harmonics are ignored. The maximum allowable EV penetration of 35/10 kV 16MVA and 10 kV 1250 kVA transformer is 50.22% and 26.19% respectively. If EVs charge in off-peak time, overloading of the cable and transformer can be avoided and the charging cost is lower. In the future work, the capacity of HV and LV power systems to adopt EV charging load in the presence of harmonic current will be modelled.

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[7] IEC 60287 Electric cables - Calculation of the current rating.
[8] IEEE C57.110-2008 IEEE recommended practice for establishing liquid-filled and dry-type power and distribution transformer capability when supplying non-sinusoidal load currents.

Appendices
Table A1 Hourly ambient temperature and residential load ratio in a typical summer day of Wuhan

| θA/℃ | 1 | 2 | 3 | 4 | 5 | 6 |
|------|---|---|---|---|---|---|
| load/p.u. | 0.26 | 0.30 | 0.30 | 0.32 | 0.40 | 0.40 |
| load/p.u. | 0.75 | 0.55 | 0.63 | 0.58 | 0.55 | 0.59 |
| load/p.u. | 0.57 | 0.60 | 0.59 | 0.61 | 0.80 | 0.92 |
| load/p.u. | 37 | 35 | 33 | 37 | 28 | 28 |

Table A2 Harmonic current of a single phase rectifier EV charger

| Harmonic order | Current magnitude /p.u. | Harmonic order | Current magnitude /p.u. |
|----------------|-------------------------|----------------|-------------------------|
| 1              | 1.00                    | 11             | 0.07                    |
| 3              | 0.32                    | 13             | 0.06                    |
| 5              | 0.18                    | 15             | 0.05                    |
| 7              | 0.12                    | 17             | 0.04                    |
| 9              | 0.09                    | 19             | 0.03                    |
### Table A3 Thermal characteristics of 10kV 400 mm$^2$ XLPE three core cable and transformers

| Parameter    | T1       | T2       | Cable   |
|--------------|----------|----------|---------|
| Δθ$_{TO-R}$  | 65 °C    | 55 °C    | θ$_{max}$ 90 °C |
| Δθ$_{e-t}$   | 30 °C    | 20.3 °C  | T$_1$ 0.2129 K·m/W |
| θ$_{T-R}$    | 125 °C   | 105 °C   | T$_2$ 0 |
| p            | 0.9      | 0.9      | T$_3$ 0.1591 K·m/W |
| m            | 0.8      | 0.8      | T$_4$ 1.1417 K·m/W |
| τ$_{TO-R}$   | 3.5 h    | 3.0 h    | I$_{rated}$ 531.77 A |
| τ$_w$        | 4.8 min  | 10 min   |         |
| R            | 5.96     | 8.76     |         |