Electric Transport Traction Power Supply System With Distributed Energy Sources

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Abstract. The paper states the problem of traction substation (TSS) leveling of daily-load curve for urban electric transport. The circuit of traction power supply system (TPSS) with distributed autonomous energy source (AES) based on photovoltaic (PV) and energy storage (ES) units is submitted here. The distribution algorithm of power flow for the daily traction load curve leveling is also introduced in this paper. In addition, it illustrates the implemented experiment model of power supply system.

Introduction
The urban electric transport is one of the most important and energy-consuming city agglomeration users. Therefore the arrangement of conditions of sustainable electric transport system development with contemporary high technology solution adoption is necessary for providing high economic growth rate and improving the quality of people’s lives. The basis of any transport system is power supply infrastructure, however, electric energy process losses in TSS converter units and traction network are 15-20 % on consumption to perform useful work [1, 2, 3]. Due to Joule-Lenz law the value of resistance losses in TPSS is:

\[
ΔP = \sum_{i=1}^{2} \left( \frac{1}{T} \int_0^T R_{TS} \cdot I_{TS}^2(t) \cdot dt \right) + \sum_{i=1}^{2} \left( \frac{1}{T} \int_0^T R_{Grid_k} \cdot I_{Grid_k}^2(t) \cdot dt \right),
\]

where \(R_{TS}\) – resistance of TSS rectifiers and transformers; \(I_{TS}\) – TSS current; \(R_{Grid_k}\) – resistance of k-th element of traction network; \(I_{Grid_k}\) – current of k-th element of traction network.
The researches of instantaneous current and voltage on DC bus made by means of measuring system based on Velleman K 8047/PCS10 in operating TSS of Novosibirsk city ground-based electric transport showed that the functional operation of TSS is an obvious pulse pattern with a power distribution variation by the hour for 24-hour period. In this regard the highest power consumption is due to morning and evening rush hour (figure 1) The load decrease these periods provides sufficient engineering-and-economical effects.

To estimate the energy losses value in TPSS an integrated index of power consumption variation is used as a form factor, given that the index is a ratio of instantaneous value to average and it can be rated as proportional to resistance losses value.

\[
K_F = \sqrt{\frac{1}{T} \int_0^T P^2(t) \, dt} \cdot \frac{1}{\frac{1}{T} \int_0^T P(t) \, dt}.
\]  

The desired degree of daily traction load curve leveling can be provided by increasing the self-supporting of TPSS. This trend is related to the application of distributed energy sources based on ES and alternative kinds of restricted power sources carrying out the power flow distribution by means of static converters.

The approaches to the integration of distributed TPSS were built in 60th years, however these researches were not evolved due to engineering constraints. New prospects of inventing more effective power systems are emerging at this point and here the number of distributed power supply systems is growing every year [4, 5, 6, 7], in addition, a greater part of generation rating is accounted for solar energy.

A number of researchers throughout the world have extensively been working over the project implementation of power supply systems by using PV and ES systems. But the theory and practice developments on co-utilization of these energy sources in TPSSs were not considered properly.

1. The circuit of TPSS

On basis of research of current distribution through electric circuit branch [1, 8], we can conclude the circuit with distributed connection of PV and ES systems will have the least energy losses proceeding from possible circuit with AES. Besides, such circuit will be more tailored to use PV systems with a large area. Figure 2 presents the circuit of single-side feed with parallel connection of contact wires in which the distributed connection of AES is used.
The structure diagram solution is suggested for combining solar batteries with ES, it is shown in figure 3. The diagram concept is based on the integration of electricity storage and primary energy sources as single modules by using power and microprocessing electronic units. [9]

The basic operating mode is the daily traction load curve leveling on account of intelligent power flows distribution between TSS and AESs. The distribution control is provided by means of AES DC/DC converter and controlled rectifier. On basis of represented figure 3 diagram the experimental power plant model was implemented into practice.

The target function is formulated for the basic operating mode:

$$f = \frac{1}{n} \sum_{t=1}^{n} \left[ \left( P_{TS} (t) - \left( P_{bat}^* (t) + P_{PV} (t) \right) \right) - \left( P_{TSS} (t) - P_{L} (t) \right) \right] - \frac{P_{TS}}{P_{TS}} \rightarrow \min ,$$  \hspace{1cm} (3)
where $P_{TS}(t)$ – TSS power, $P_{Bat}^*(t)$ – ES discharge power, $P_{PV}(t)$ – PV power, $P_L(t)$ – load traction power, $\overline{P_{TS}}$ – TSS average power for 24hour period.

The expression (3) introduces the optimization function by minimum criterion dispersion of load TSS. The average value of this load for 24hour period is the mathematical expectation value. Three control actions are emphasized in compliance with the control object structure.

1. **Control signal of operating mode circuit.** Switching-over from day mode to night one and backwards.
2. **PWM signal for MPPT.** Adaptive maximum power tracking in output of PVs is carried out on basis of Fuzzy Logic.
3. **PWM signal to control load distribution between energy sources.** The duty cycle signal is proportional to the capacity credit and it may be used to transmit from AES to the load. This part of power is defined in accordance with a target function. To match the output power the out- of- level reverse control signal is fed to an active rectifier. Thus, the following ratio is correct:

$$P_{TS} = (P_{PV} + P_{Bat}^*) \cdot \frac{D_1}{D_2},$$  \hspace{1cm} (4)

where $D_1$ – duty cycle of control signal by means of AES DC/DC converter, $D_2$ – duty cycle of control signal by means of controlled rectifier.

At day mode the charge power is equal to the difference of PV output power and power transmitted to the load due to constraints on maximum charging current rate. Whereas, the PV output power is always supported at maximum level. At night mode the system goes into storage charge from the grid due to an active rectifier, the charge power is defined as:

$$P_{Bat} = \frac{E_{Bat, MAX} - E_{Bat}}{T_{CHI}},$$ \hspace{1cm} (5)

where $E_{Bat, MAX}$ – maximum ES capacity; $E_{Bat}$ – ES state of charge; $T_{CHI} = 1700$ c – charge time.
At day mode the control function is the definition of output power storage value. The solution of the given task and also the charge storage task is presented as algorithm in figure 5.

The load curve leveling principle. The ES charge is carried out at night time hours at zero power consumption (its price is the lowest) as well as at PV power redundancy. The load factoring is provided on account of power generated by PV combined with storage power during the periods of low or zero energy consumption and during the periods of PV power redundancy. This PV energy use is more rational on peak busy hours rather than on its generation period.

3. Experimental results
The experiment model of power generation system based on the integration of PV system, ES and grid is implemented and tested as part of presented solutions. The control program is implemented in Lab View.

To test and demonstrate the operation by means of program-controlled simulator the daily load curve with form factor 1.3 is modeled. The derived oscillograms of currents and voltages on the load are shown in figure 6.a. The oscillogram of PV output power is shown in figure 6.b. These oscillograms demonstrate the experiment model operating results illustrated in figure 6.c and d. As a result of experiment model test on load leveling the form factor of the grid equal to 1.016 is received.
Conclusion

The paper presents the researchers’ results on the load leveling of power supply system for urban electric transport by means of PV and ES systems. The distributed connection circuit of these AESs to the traction network for reduction energy losses is proposed here. The experiment model of power generation system and the experiment control program are implemented. The control program is based on the presented algorithm of distributed power flows. Further the program performs the circuit modes switching and tracking PV maximum output power based on Fuzzy Logic. The test on load curve leveling is conducted. At the same time the storage batteries with energy capacity above the mark are used. As a result the form factor of the grid daily-load curve equal to 1.016 is received. Taking into account the fact that the form factor is proportional to resistance losses value then the power loss reduction amounts to as much as 22%.

To improve the program operation it is necessary to calculate the charge time based on statistic data and also update the algorithm by the module of charge and discharge integrator in accordance with the quality management program assessment.

The objective of the future research is a ratio determination between PV power and ES capacity, whereby, the rational rate of leveling traction load curve will be provided. The TPSS with distributed connection circuit of AESs for the light rail transit line in Novosibirsk will be the research object.

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