The Auxiliary Systems Influence on the Energy Efficiency of Diesel Electric Locomotives

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Abstract— This paper present review of the auxiliary systems used in diesel-electrical locomotive. Moreover, the paper presents a brief comparison of two diesel-electric shunting locomotives used in Estonian rail roads nowadays.

I. INTRODUCTION

With a logistic development speed, load and the efficiency of vehicles are increasing. But the ways of transporting are not changing. The railroads still hold a niche in the world logistic there was a number of different locomotive types used historically. Nowadays, the mostly used locomotive type is a diesel-electrical locomotive. Due to some advantages they are used. Firstly a compact size of diesel-electrical transmission, while with a pure mechanical transmission from engine to wheels a large gear is required. Secondly, with a generator-to-motor traction system wide range of operating speeds are available [1]. Moreover, in diesel-electrical locomotives the diesel internal combustion engine can be run at the most optimal mode, to provide the maximal efficiency and be possibly friendly to environment.

The main improvement challenge of diesel-electrical locomotive is increasing the power factor of the traction system. The efficiency of generator-to-motor traction system is low, because of the large number of used electrical machines (mainly the low efficiency brushed -DC machines). The high technology jump in the field of power electronics in the last few decades gives a push to using the power electronic devices in high power vehicles area. The main benefits of the power electronic devices are the high efficiency and the smaller size in comparison with generator-to-motor system. The traction system of the diesel-electrical locomotive is not the only part that could be improved. This paper presents a list of typical auxiliary devices used in diesel-electrical locomotive and its improvement possibilities.

II. DIESEL-ELECTRIC SHUNTING LOCOMOTIVES USED ON ESTONIAN RAILROADS

The diesel-electrical shunting locomotives are used mainly at rail stations to compound and demount the trains. They are optimized for shunting operations and their duty diagrams are usually different from other types of locomotives (passenger and freight locomotives) [2]. On Estonian railroad the shunting locomotives play a very important role, in that case research and improve possibility development in that field is interesting. Since second half of 2013 fifteen new China origin shunting locomotives DF7G-E should replace Czech origin shunting locomotives CME3 [3].

DF7G-E and CME3 are both a diesel-electrical locomotives, but have different transmissions. The CME3 has a DC-DC transmission, without converter between generator and traction motors. 10-pole separately excited DC generator feeds six 4-pole series DC motors. DF7G-E AC-DC as the main transmission and AC as an auxiliary transmission. The main alternator employs brushless excitation and axle-hung rolling bearing structure is used for motor assembly.

More detailed DF7G-E and CME3 locomotives are compared in Table 1.

<table>
<thead>
<tr>
<th>Type of locomotive</th>
<th>DF7G-E</th>
<th>CME3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>16</td>
<td>15*</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>China CNR</td>
<td>ČKD</td>
</tr>
<tr>
<td>Year of manufacture</td>
<td>2003</td>
<td>1980-87</td>
</tr>
<tr>
<td>Axle arrangement</td>
<td>Co-Co</td>
<td>C-C</td>
</tr>
<tr>
<td>Diesel engine output, kW</td>
<td>2200</td>
<td>993</td>
</tr>
<tr>
<td>Rotation frequency, rpm</td>
<td>1000</td>
<td>750</td>
</tr>
<tr>
<td>Number of cylinders</td>
<td>V-12</td>
<td>R-6</td>
</tr>
<tr>
<td>Bore of cylinder, mm</td>
<td>240</td>
<td>310</td>
</tr>
<tr>
<td>Stroke, mm</td>
<td>275</td>
<td>360</td>
</tr>
<tr>
<td>Power convertor type</td>
<td>AC-DC</td>
<td>DC-DC</td>
</tr>
<tr>
<td>Working mass, t</td>
<td>138</td>
<td>123</td>
</tr>
<tr>
<td>Length, m</td>
<td>19.4</td>
<td>17.2</td>
</tr>
<tr>
<td>Speed limit, km/h</td>
<td>100</td>
<td>95</td>
</tr>
<tr>
<td>Minimal curve radius, m</td>
<td>100</td>
<td>80</td>
</tr>
<tr>
<td>Traction clutch, kN</td>
<td>317</td>
<td>226</td>
</tr>
<tr>
<td>on the speed, km/h</td>
<td>15.8</td>
<td>11.4</td>
</tr>
<tr>
<td>Fuel reserve, l</td>
<td>6000</td>
<td>6000</td>
</tr>
<tr>
<td>Total water volume, l</td>
<td>1100</td>
<td>1100</td>
</tr>
<tr>
<td>Total oil volume, l</td>
<td>850</td>
<td>650</td>
</tr>
<tr>
<td>Total sand volume, kg</td>
<td>500</td>
<td>1500</td>
</tr>
</tbody>
</table>

Shunting locomotive is mainly used for marshalling and shunting operations in large and medium sized marshalling yards. Such operations require shunting locomotives to work in an unstated mode, with repeated take-offs and accelerations. There are three main operations modes for a shunting locomotive: a full load operation mode; a partial load operation mode and an idling mode [4]. As it can be seen from the Table 1, the power of the traction motors is almost equal to generator power. In the on-load operation mode the part of auxiliary devices is insignificant, but in the continuous idling mode this power could be notable.

The real working mode of switching locomotives is presented in Fig. 1. These measurements have been taken from shunting locomotive type TEM18, over a period of five hours. As it can be seen from the diagram, the locomotive has not been working with full load, the rated power of TEM18 is 882 kW. The on-load mode of locomotive is interchanging
with idle modes. The more detailed load distribution is shown on histogram presented in Fig. 2.

Fig. 2. Histogram of shunting locomotive TEM18 duty cycle

III. TYPICAL AUXILIARY SYSTEMS OF DIESEL-ELECTRICAL LOCOMOTIVES

Locomotives have different auxiliary equipment on-board. The main purpose of this equipment is to provide the stable work of traction system by cooling heating mediums, oiling friction surfaces and stable fuel feeding. Perhaps the most important of the auxiliaries of shunting locomotives is the equipment for starting. An internal combustion engine (ICE) is not usually self-starting so an auxiliary machine is required to start it and it’s always a challenge to reduce the pollution during the ICE start.

Czech origin locomotive ČME3 was designed in 1980s when DC motors were in common use. Chinese locomotive DF7G-E is a modern locomotive which uses DC-link for traction motors and AC-link for the auxiliary systems. There are few typical auxiliary parts used in locomotives. The auxiliary systems of shunting locomotives which mostly use electromechanical and pneumatic systems depend on the type of locomotive. Each auxiliary system has at least one pump, the power and dimensions of pumps depend on model of the locomotive and the function of the pump.

A. Oil system

Oil system is required for storage, filtering, cooling and delivery of pressured oil to all friction parts of the locomotive. Oil system contains main and reserve oil tanks, oil-priming pump, oil filters and pipes.

The oil-priming pump gets the power from the crankshaft while diesel engine is working and from the electric drive while starting.

Water cooling is used for cooling of the oil system and oil pipes. The oil-to-water heat exchanger is used for this purpose.

B. Water system

Water system could be divided on two parts. First one is used for cooling of motionless parts of locomotive, like cylinders head etc. Another one is used for operator’s cabin heating, sometimes to keep the fuel from freezing. The same circulation circuit are used in both cases. But the derivation that heats the fuel tank could be switched on and off, depends on feature necessity.

The pumps used for water circling are centrifugal type pumps.

C. Fuel feed system

The fuel feed system provide the diesel delivery to the ICE, moreover it is used for fuel storage, filtering and fuel preheating. Fuel feed system includes fuel tank, fuel preheater, fuel boost pump, coarse fuel and secondary fuel filters, injection pump assembly, sprayer and pipes.

Fuel reserve is stored in a fuel tank, the volume of the fuel tank depends on the locomotive’s model and type of diesel engine. The fuel boost pump is required for fuel delivery from fuel tank to fuel fold of the engine. Fuel injection pumps are also used for diesel injection into sprayer. Usually diesel engine has a number of fuel pumps equal to a number of cylinders, one for each cylinder, accordingly, ČME3 locomotive has 6 fuel pumps and DF7G-E has 12 fuel pumps. Fuel tank and whole fuel feed system should be leak-proof to avoid fuel from pollution.
D. Air supply system

Air supply system intakes air from the atmosphere, filters, cools and delivers it to the ICE with required pressure and quantity. Intake of the pressured air into the diesel engine increases the volume of fuel that could be burned, which means the power of diesel engine is increasing, but overall dimensions are not changing.

Puffing is used to clear an engine piston from the waste gases after the fuel combustion. The air intake and puffing is required for stable work of diesel engine.

Different cooling fans could be classified as the part of air supply system, as well. Fans are used for electric machines (traction generator and traction motors) cooling. Moreover, the fans are also used to increase the cooling time of oil and water heatsinks.

E. Braking system

Typically locomotives use pneumatically operated brakes. Which means the compressed air is used for locomotive and train braking. But the structure and operating mode of braking system is different from the rest of air supply system, that’s why it should be watched separately.

The breaking system is one of the parts of a shunting locomotive that can be notably modernized. The temperature of the compressed air is usually higher than the ambient temperature, moreover, the mechanical braking is allied with friction, that increase the temperature of braking parts, thus additional cooling system is required, especially for the shunting locomotives, according to its operating mode.

Usage of electrical transmission and DC traction motors allows to apply some electrical braking modes. The simplest electrical breaking is a resistance braking, when the breaking resistance is connected in series to DC motor armature. The disadvantage of that type of breaking is warming of the breaking resistance, which a results in the heat losses and lower efficiency. During the dynamic braking of the DC motor the armature winding is needed to be disconnected from the supply. High armature currents of traction motors make using of dynamic braking not reasonable, because of high cost of the switching equipment. Maybe, the most useful braking mode is the regenerative braking. In this braking mode the traction motor operates as a generator, that means, it producing the electrical energy. This energy could be stored in some energy storing device, the most common is battery pack (that already in used in locomotives for running up), or in some modern solutions like supercapacitor, flywheel, SMES.

IV. USING OF AUXILIARY DEVICES IN CONNECTED TO GRID LOCOMOTIVE

Total power of ČME3 is 993 kW and almost 85 kW is a power required for auxiliary devices, it’s almost 10% of full power of locomotive [5]. Moreover, often repeated take-offs and accelerations needs the starting-up equipment to be in the idling mode. In this case the energy consumption is already notable and makes sense. If the locomotive works closely to a rail station very interesting looks the locomotive-to-grid (L2G) solution, similar to plug-in hybrid electric vehicles (PHEV). Sure the diesel-electric locomotive is much more powerful than any other PHEV and that reveals some benefits of L2G system:

- The connected to the grid locomotive could feed the auxiliary devices directly from the grid. No on-board energy sources are required.
- Using power electronic converters in powertrains allowing using it as a STATic synchronous COMpensator. The main application of STATCOM is to compensate the reactive energy consumption, so the L2G system could be used for improving of the parameters of the grid.
- The fast energy flow control allows using the plug-in powertrain as a parallel active filter. The main application of the active filter is to regain the magnitude of parameter to sine wave and reducing harmonic influence. Decreasing of the harmonic influence is one of the actual problems of today’s electric grid.
- The diesel-electrical locomotive uses diesel fuel as it primary energy source and electric batteries as an additional energy storage source. These features allow to implement the plug-in powertrain as a portable power plant.

There is no complex modernization required for plugging the diesel-electrical locomotive to the grid. Moreover, nowadays used powertrains can be updated. Using electrical vehicles and hybrid electrical vehicles in connection with electrical grid brings new features to the electrical grid. Ability to use plug-in vehicle allows to make the electrical grid more widely distributed.

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