RECIPROCATING ENGINES AS A SOURCE OF FLEXIBILITY IN A POWER SYSTEM

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Summary. In recent years, flexibility of power generation systems – understood as their ability to perform quick start-ups, shut-downs and load changes in possibly broad range and with small loss of efficiency – has been seen as increasingly important. This is due to increased popularisation of wind and solar power generation systems, which operate at variable and not fully predictable output. This creates a demand for power sources able to quickly replace temporarily lost (reduced) output of renewables, which would be characterised by low fixed cost (due to relatively low capacity utilisation factor). The paper presents the newest technical achievements in the field of large reciprocating internal combustion engines used to meet this kind of demand – including technical parameters of current and prospective solutions, as well as operating experience from plants used to provide backup power, along with results of tests confirming ability of engine-based power generation systems to provide ancillary services (primary and secondary frequency control). Also discussed are results of selected techno-economic analyses which highlight system-level benefits resulting from building high-flexibility sources in various power systems, and economic conditions necessary to adopt such technologies. Incentives and obstacles for development of such technologies at the Polish and European energy markets are presented along with different commercial concepts for plants ensuring power flexibility based on examples from different countries.

1. INTRODUCTION

Issue of generation flexibility is becoming increasingly important in modern power systems. This fact is primarily attributable to ever-increasing share of intermittent renewable power generation from sources such as wind and solar radiation. Such sources, while environment-friendly, cannot be dispatched by human operators, and therefore operate independently from the power system load patterns.

A the same time in most developed countries they are legally prioritised, and – save for emergency situations – must be allowed to run if able. Such a situation creates new challenges for conventional power generation, which must be able to cope with additional load changes. Particularly difficult are situations, when output from renewable generation drops at the same time, when system load grows – for example during evenings in systems with high share of photovoltaic power plants (

Fig. **1**) or if wind stops blowing during early morning of a working day in a system with lots of wind generation (see Fig. **2** below).

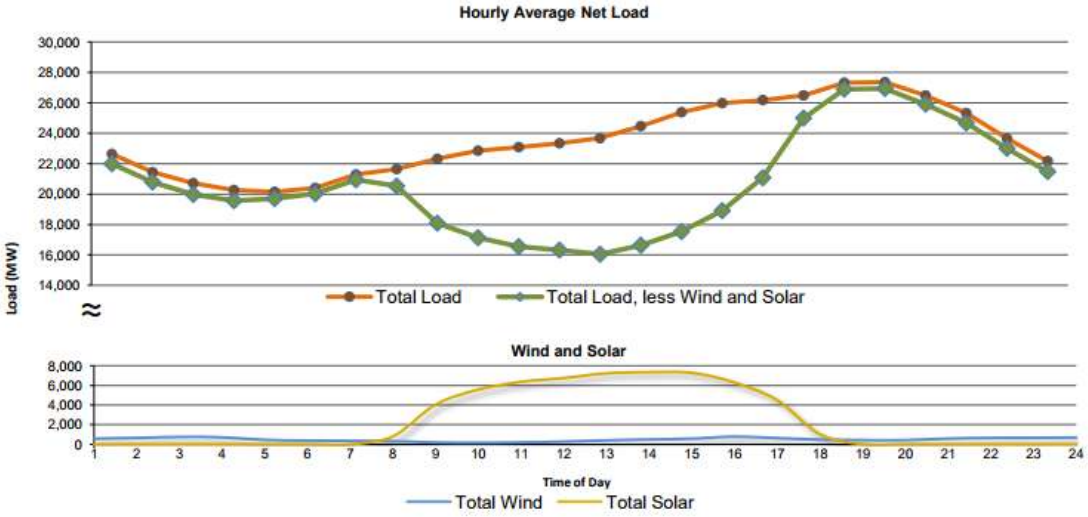

Fig. 1. Need for flexibility demonstrated in California on 22 October 2016. Output drop from solar plants in the evening causes an unusually (for that system) steep ramp for dispatchable sources. Conventional power plants must cope with the ramp rates which had not existed in this system before introduction of considerable solar PV generation capacity. Such a shape of conventional generation load, typical for systems with high share of PV, is now known as "the duck curve" [1]

2. RECIPROCATING ENGINES IN POWER INDUSTRY – CURRENT STATUS

Until recently, applications of reciprocating internal combustion engines in commercial power industry had been quite limited. Engines were commonly used only in relatively small generating sources, particularly combined heat and power plants, with a scale rarely exceeding some 20 MW. Liquid fuel engines had also been used in larger plants running on heavy fuel oils, for example in South America, Middle East or on some remote islands (e.g. in Greece). However, since the turn of the century, applications of engines have expanded greatly.

Reciprocating engines used in modern commercial power industry (in plants exceeding roughly 5 MW of electrical output) are in vast majority turbocharged, four-stroke medium-speed[1] engines, with unit output of 4 to 20 MW. Those engines are directly coupled to synchronous medium voltage generators. Three main types of engines are used:

- Spark-ignited gas engines, designed exclusively for gaseous fuels
- Diesel engines, designed exclusively for liquid fuels
- Dual fuel engines, capable to operate on either liquid or gaseous fuels. Dual fuel engines may switch between liquid and gaseous modes during operation and under load. In gas mode, the ignition is effected by a small (ca. 1%) pilot dose of liquid fuel injected towards the end of the compression stroke.

[1] Speeds used in 50 Hz power systems are 500, 750 or 1000 rpm.

General principle of building power stations using such engines are identical, regardless of the engine type. Typically plants consist of many parallel, independent engine-generator sets, with the common part limited to high-level automation systems, fuel supply system and power off-take.

Gross efficiencies of modern engine-generator sets vary from 45 to 49%, depending on the output class and type of engine. Those are the highest efficiency levels achieved by simple cycle machinery available today. Other distinctive features of reciprocating engine technology include:

- Very short start-up time. For the state-of-the-art gas engines, start-up time counted from start command to full output, is just 2 minutes (with synchronisation and load acceptance within 30 seconds) [2][3]. For liquid fuel engines this time is even shorter.
- Very short stopping time – 1 minute for load reduction (if generator breaker is not tripped instantly) and up to 80-90 seconds for the shaft to stop. After stopping, a gas-fired generating set is ready for restarting within 5 minutes (this time is needed to purge the exhaust system of possible flammable gases, it is not needed in liquid-fuel engines) [2][3].
- Low minimum load. For a single engine it is typically 20-30% of nominal output. This allows obtaining a very wide operating range for an engine-based power plant, especially if numerous engines are installed.
- Low sensitivity to variable ambient conditions. In particular, ambient air temperature does not impact output or efficiency of an engine up to the level of approximately 35-40°C. Only above such levels, output and efficiency may be restricted, due to impossibility of cooling down the air compressed in the turbocharger to the desirable value [4].
- No impact of start-ups and shut-downs on maintenance schedule – in engines there are no extra “equivalent operating hours” counted for frequent startups.

At the same time, the engine-based plants are characterised by low investment cost, comparable to open cycle gas turbines (OCGTs), and considerably lower than combined cycle gas turbines (CCGTs). In European conditions the cost may be evaluated upon the recent investment of the Estonian transmission system operator Elering AS, which has built a 250 MW dual-fuel emergency reserve power plant in Kiisa near Tallinn. The value of EPC construction contract, carried out in 2011-2014 (the plant was built in two phases) was EUR 129 m [5]. The total cost of the project declared by the public investor was EUR 135 m [6]. This yields a specific cost of installed electrical capacity of some EUR 540,000 per megawatt.

On the other hand, engine-based plants are characterised by slightly higher maintenance cost than either OCGTs or CCGTs. Reciprocating engines also emit more nitrogen oxides. In case of spark-ignited gas engines it is possible to achieve compliance with the up-to-date European

emission standards (i.e. the Industrial Emissions Directive, IED[2]) with primary methods (by optimising combustion process), this causes reduction of engine efficiency of some 1.0-1.5 percentage point. In practice investors in most cases choose to use exhaust gas cleaning in form of selective catalytic reduction (SCR), while keeping full electrical efficiency. For dual-fuel and diesel engines, SCR is always needed to meet modern emission standards for commercial plants[3].

Because of this set of features, reciprocating engines are most suitable for power stations with relatively low capacity factors (intermediate- and peak-load), where low fixed generation cost resulting from low investment cost is relatively more important than variable generation cost, higher than in case of CCGTs due to lower efficiency and higher maintenance cost. In such applications also beneficial is very high dispatch flexibility – fast start-ups, load changes and shutdowns. These enable the operator to more efficiently utilise price volatility on intra-day or real-time electricity markets. For those reasons, engine technology has already been adopted for a number of large (above 100 MW) gas-fired peaking power plants, especially in the United States.

The engine technology also gets increasingly popular in larger scale commercial combined heat and power (CHP) plants, which are also expected to operate intermittently. Such operation, enabled by dynamic features of engines and utilisation of heat storage tanks, also enables operator to generate profits on volatile intra-day electricity markets. Examples of such plants include the facility of Stadtwerke Kiel (190 MW electrical + 192 MW thermal)[8] or Kraftwerke Mainz-Wiesbaden (100 MW electrical + 90 MW thermal) [9], both now under construction in Germany. Yet it is worth noting, that in case of high-efficiency cogeneration, engine-based plants may also be competitive against CCGT solutions also when operating in baseload, and even at outputs of several hundreds megawatts, if the plant is dimensioned according to the heat demand. In case of such a plant, higher electrical efficiency of a CCGT solution is compensated by lower electrical output needed at an engine-based plant, and lower cost of that installed capacity. A high-efficiency CCGT CHP unit with a heat output of some 250 MW has an electrical output of some 420-450 MW, while an engine-based plant serving the same heat load would only have electrical capacity of some 300 MW, and at lower cost per megawatt. This leads to a considerably lower total investment cost and may make the engine-based solution competitive [10]. Then in case of CHP plants below 100 MW, the difference between electrical efficiency of a CCGT solution (when operating in cogeneration) and engine-based solution becomes negligible, which generally makes engines the preferred solution [11]. Issue of mutual competitiveness of engine- and turbine-based solutions is further discussed in [12].

[2] Note that NOx emission levels for gas engines specified by the IED are still considerably higher than those for gas turbines [7].

[3] This is not applicable to emergency plants though, so the aforementioned Kiisa Emergency Reserve Power Plant does not have any SCR system.

Other applications of large engine systems result from their ability to combust special fuels (e.g. poor quality heavy oils or raw vegetable oils) and their resistance to extreme ambient air temperatures. Engines are also used in floating power plants, quite popular in South America.

At present, the largest power plant based on reciprocating engines in the world is the IPP3 facility in Jordan, commissioned in 2014, with an installed capacity of 632 MW (reduced to 573 MW in maximum design weather conditions, at ambient air temperatures considerably above 50°C). This plant is based on dual-fuel engines – initially it is operated at heavy fuel oil, but eventually (after a gas pipeline is completed) it will switch into operation on natural gas. The plant is operated to cover peak and intermediate load [13][14]. The largest engine-based plant in Europe is the already mentioned Kiisa Emergency Reserve Power Plant at KIisa, Estonia.

3. EXPERIENCE IN DYNAMIC OPERATIONS

As already mentioned, large engine-based power plants with outputs exceeding 100 MW have been operated in the United States of America for more than ten years. One example of such a plant is the Plains End Power Station located in the area of Denver, Colorado. It consists of two units. The Plains End I plant consists of twenty Wärtsilä 18V34SG engine-generator sets with a combined output of 113 MW, and was commissioned in 2002. The Plains End II unit consists of fourteen newer Wärtsilä 20V34SG sets, with the combined output of 118 MW and was commissioned in 2008. Both units are used for intermediate load operation, as well as peaking and emergency response. They enable stabilisation of the Colorado's power grid, where large wind power capacity is connected. Typical annual capacity utilisation time is 1500 to 3000 hours, and the engines are started up several hundred times per year. When starting up from preheated condition (maintained with electric heaters, 2 × 30 kW per engine, although typically operation of just half of that capacity is sufficient), the plant may reach full nominal output within less than 8 minutes of the startup order[4]. Typical utilisation of the plant's dynamic features in shown in Fig. 2. More information about this plant and its operation is presented in the study [15].

Excellent dynamic features of reciprocating engines is also utilised in CHP plants, especially in Denmark. Small engine-based municipal CHP plants equipped with heat storage tanks (and recently also with electric boilers, which enable economical heat generation when electricity prices get very low or even negative) are very popular in that country. These plants are dispatched according to variable prices on electricity markets (day-ahead, intra-day or balancing). An example of such a facility is the Skagen district heating plant commissioned in 1998.

[4] This is slower than state-of-the art technologies mentioned in the previous section, but this is due to the age of used technology.

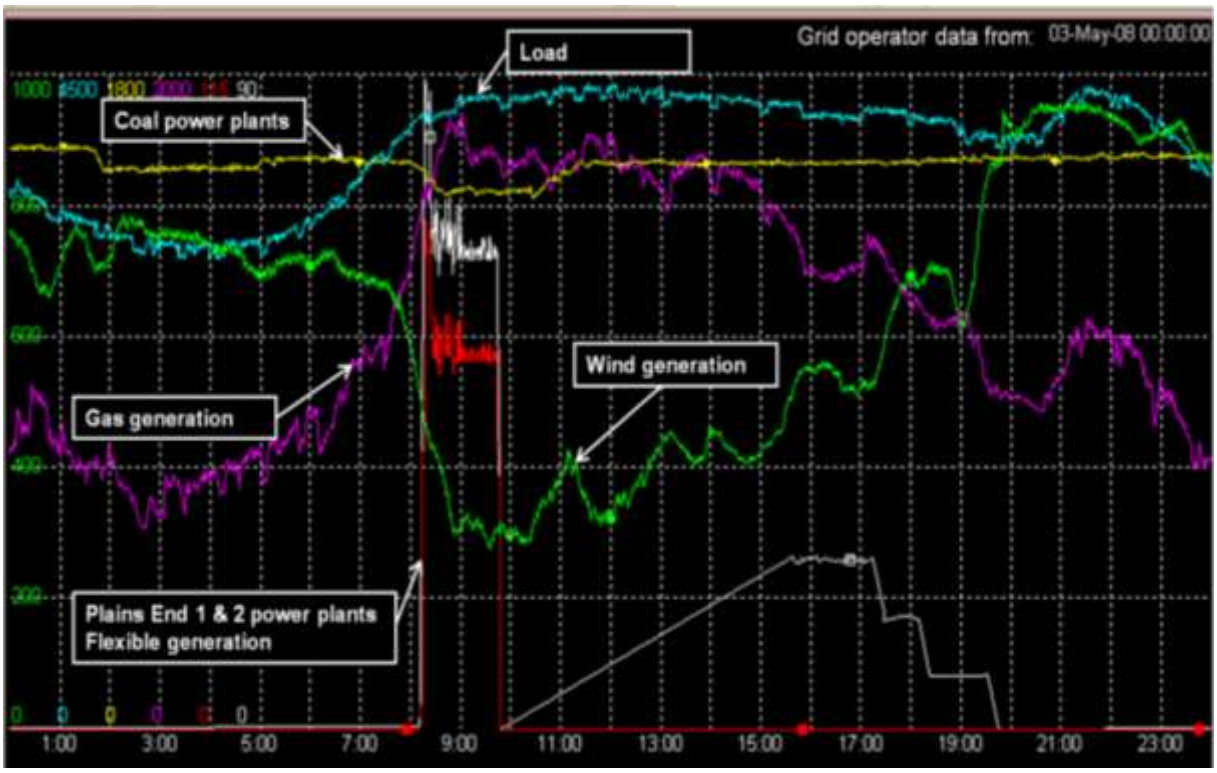

Fig. 2. Operator's graph from Colorado's grid operator, showing how the Plains End Power Plant is dispatched. The graphs shows rapid startup of Plains End (red curve) shortly after 8 a.m., in a situation when wind generation (green curve) is dropping, while the system load (light blue curve) is rising. The engine-based plant is used to cover the capacity gap, until other more efficient but less flexible sources may raise their output sufficiently. Note different scales for different curves, shown in respective colours in upper-left corner.

Skagen plant consists of three Wärtsilä 18V28SG units with a total output of 12.9 MW electrical and 16 MW thermal, a heat storage tank with a capacity of 250 MWh and a 10 MW electric boiler. In this case the engine-generator sets are dispatched exclusively according to the electricity prices, and typically start and stop several times per week. Fig. 3 shows operation of this plant in a selected week of February 2015, when the engines were started five times, each time for several hours. During those periods, its heat output exceeded current load, and the excess heat was accumulated in the storage tank for later use [12][5]. Similar operational regime is followed by other Danish engine-based plants, for instance in Ringkøbing or Jelling.

Another example of cyclic CHP plant operation can be seen at Újpalota CHP plant in Budapest, Hungary. This plant with three engines and a total output of 23.1 MW electrical and 19.2 MW thermal, commissioned in 2002, was originally designed as baseload unit and had to change its regime of operation to adapt to changing market environment. Currently its engines are started and stopped up to twelve times a week [12].

[5] History of Skagen CHP plant operation is followed at http://www.emd.dk/plants/skagen/; historical data is also available.

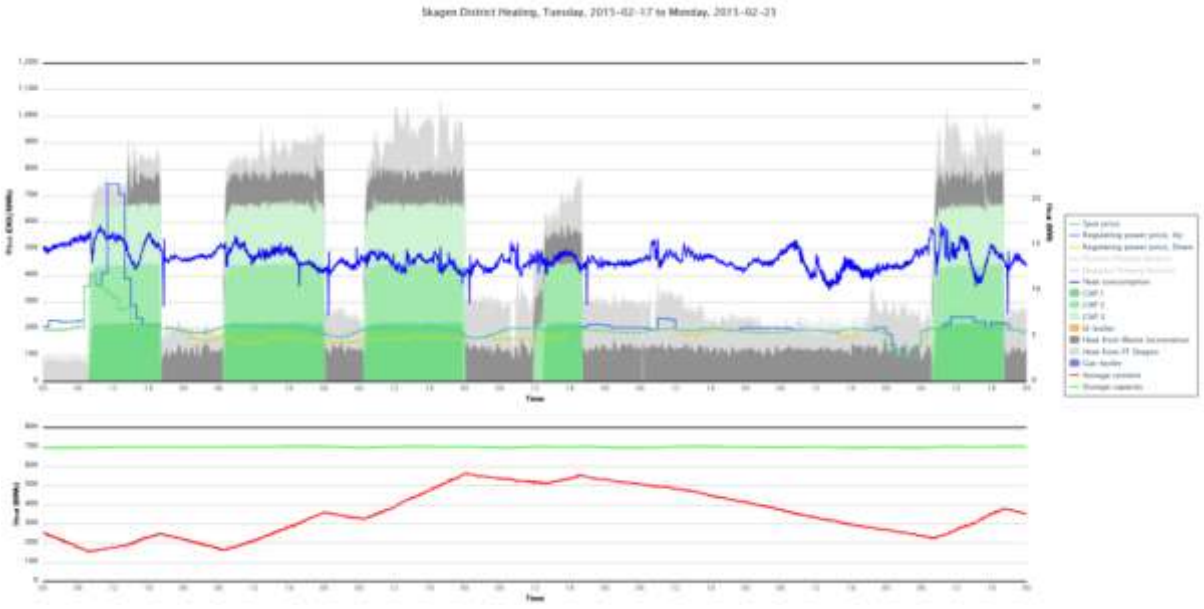

Fig. 3. Operation of the Skagen municipal heat supply system during one week of February 2015. Operation of engine-generator sets is shown with different shades of green. Light grey is the waste heat from local industrial facility and dark grey – from a waste incineration plant. Dark blue curve shows total heat demand in the system. Lower part of the chart shows how the heat storage tank is charged and discharged (light green line at the top is its total capacity).

4. RECIPROCATING ENGINES AS FREQUENCY CONTROL ASSETS

Providing proper frequency control reserves, especially primary and secondary, is essential for ensuring stability and reliability of a power system. Demand for this kind of reserves is nothing new, however increase of intermittent renewable capacity does increase demand for control reserves, as described in [16]. At the same time reduced share of conventional generation makes it more difficult to provide those reserves from traditional power stations, limited by their minimum loads and load change rates. This creates a need for new types of capacity, which could offer considerable frequency control reserves, while not necessarily operating at high load.

Reciprocating engines' ability to provide frequency control may not seem obvious, as even the largest engines used in commercial power engineering have relatively low inertia of rotating masses. However, recent studies and operational experience confirm, that not only this is possible, but engine-based plants may be better at providing reserves than other types of sources.

In 2011-2012 Dutch technical advisory company KEMA carried out a theoretical study to check how power plants based on reciprocating engines would perform as sources of frequency control reserves. The analysis was based on modelling of the Dutch power system

assumed to operate in the island mode. The study has fully confirmed that engine-based plants may provide both primary and secondary frequency control; moreover secondary control might even be provided by stationary engines (i.e. not by spinning reserve), provided that sufficiently flexible engine models are used (thanks to the fact, that such generating sets may synchronise and accept load within 30 seconds, which coincides with the secondary reserve activation time required by most grid codes). Frequency control by engine plants has also been field tested at a number of actual power stations, for example at an industrial power plant operated by HG Enerji in Gediz, near Izmir, Turkey. The plant has successfully demonstrated ability to provide primary control reserve of 10% of its nominal capacity as per requirements of the Turkish transmission system operator TEİAŞ (reaction time of 2 seconds, full reserve activated within 30 seconds). This plant, as well as other Turkish engine-based plants are now providing primary and secondary control on daily basis, and will continue doing so, after requirements for secondary reserve are tightened (activation time reduced from 15 to 5 minutes) [17].

5. FLEXIBLE POWER PLANTS IN A POWER SYSTEM – ECONOMIC BENEFITS AND CHALLENGES

Because of the reasons described before, introduction of highly flexible sources into a power system may bring technical benefits related to the balancing process – in extreme cases it may even prove indispensable due to increasing load variations for conventional generation. Published studies indicate that deployment of such capacities might also bring considerable economic benefits on system level. This is attributable to the fact that introduction of highly flexible plants, callable of very fast startup, characterised by high efficiency and able to change their load quickly without significant efficiency reduction enables more optimal dispatch of other, less flexible power units operating within the same system. This in turn leads to lowered costs of operation of those other sources (as they might operate closer to their nominal outputs), and lowered costs of system balancing.

In 2013 Redpoint Energy consulting company performed a study of potential savings in case of introducing major capacity of highly flexible power stations into the British power system . It was calculated that if instead of building 4800 MW of already planned CCGT capacities, the same output was installed in gas sources of higher flexibility, the total annual cost of power generation in the UK could be reduced by 381 million GBP in 2020 and 578 m GBP in 2030, if the system otherwise develops according to current baseline scenarios. In case the "high wind" scenario of the British power system development were to be realised, the savings would grow to 545 m GBP in 2020 and 1.5 bn GBP in 2030. In 2012-2013 KEMA DNV carried out a similar study for the power system of California [19], and these demonstrated that introduction of high-flexibility sources could reduce total generation costs by 273-352 m USD in 2020, depending on grid development scenario. On top of that, there would be a reduction of 16-30 m USD reduction in the cost of ancillary services – compared to the scenario when those services are provided by gas turbines, and even 592-777 m USD in

comparison to load shedding. In both those studies, high-flexibility capacities were defined in such a way, that reciprocating engines would in practice be the only currently available fuel-based technology to meet the assumed parameters.

Those impressive figures apply to the total costs of entire power system. This, however, does not automatically translate into benefits for an individual investor. One of the most important reasons is that the cost of system balancing – at least in unbundled markets – is incurred by the transmission system operator and then duly transferred to final users. At the same time, the system operator has no impact whatsoever on the energy mix. It is legally obliged to ensure the balancing with existing resources, and then allowed to forward the resulting cost. Legal regulations existing in most power systems do not promote flexibility in any meaningful way; capacity markets do not grant higher value to more flexible capacity. Because of that, there is no incentive for individual investors to build such plants. Thus it seems reasonable to at least consider certain incentive schemes or market design solutions, which would promote construction of highly flexible capacities – as long as the cost of those incentives is lower than potential benefits from the capacities, this would lead to overall benefits for the economy. Such possible incentive mechanisms will be a subject of further studies.

6. CONCLUSIONS

Current state of the art in the field of industrial reciprocating engines allows for their utilisation in small- and medium-scale commercial power generation facilities. Such plants are characterised by outstanding operational flexibility, combined with high efficiency and low fixed costs, which makes them excellent solution for intermittently operated power stations. In the near future, such plants will become increasingly useful (or even indispensable) to ensure smooth integration of intermittent renewables. Moreover it may be demonstrated that use of such flexible capacities may lead to considerable reduction of costs in entire power systems. Yet current designs of energy markets in most Western countries, including European Union, does not create incentives for such investments, which might lead to not using considerable potential created by recent advances in engine technology.

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SILNIKI TŁOKOWE JAKO ŹRÓDŁO ELASTYCZNOŚCI W UKŁADZIE NAPĘDOWYM

Słowa kluczowe: silniki tłokowe, elektrownie szczytowe, elektrownie interwencyjne

Streszczenie. W ostatnich latach obserwowany jest wzrost znaczenia elastyczności instalacji energetycznych rozumianej jako zdolność do szybkiego rozruchu, odstawienia oraz zmiany bieżącego punktu pracy w możliwie szerokim zakresie i z możliwie niewielką utratą sprawności. Jest to związane z coraz większym rozpowszechnieniem źródeł wiatrowych i słonecznych, których moc wykazuje istotne i nie w pełni przewidywalne wahania. Tworzy to zapotrzebowanie na instalacje energetyczne zdolne do szybkiego zastępowania czasowo utraconej (obniżonej) mocy źródeł odnawialnych, charakteryzujące się jednocześnie możliwie niskimi kosztami stałymi (z uwagi na względnie niski współczynnik zainstalowania mocy zainstalowanej). W artykule przedstawiono najnowsze osiągnięcia techniczne w obszarze rozwoju gazowych silników tłokowych wielkiej mocy wykorzystywanych do zaspokojenia takiego zapotrzebowania – w tym parametry techniczne obecnie stosowanych i perspektywicznych rozwiązań, a także doświadczenia eksploatacyjne z instalacji wykorzystywanych do rezerwowania mocy oraz wyniki prób potwierdzających zdolność instalacji silnikowych do świadczenia usług systemowych (pierwotnej i wtórnej regulacji częstotliwości). Omówiono także wyniki wybranych analiz techniczno-ekonomicznych wskazujących na korzyści systemowe z zastosowania jednostek wytwórczych o wysokiej elastyczności w różnych systemach energetycznych oraz warunki ekonomiczne niezbędne dla wdrożenia takiej technologii. Wskazano czynniki sprzyjające oraz przeszkody w rozwoju omawianych technologii w warunkach polskiego i europejskiego rynku energii, a także różne modele funkcjonowania instalacji zapewniających elastyczność mocy wytwórczych w oparciu o przykłady z różnych krajów.

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