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Reliability of Divided Small Electric Energy System

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***Abstract*—Reliability is one of the most important factors of electrical energy system. This paper presents analysis of reliability of electrical energy system and divided small electrical energy system. To meet stated requirements of reliability is needed to increase energy supply reliability by increasing equipment reliability, distributing energy generation and creating smaller electric energy systems during fault period. The small electrical energy system creation impact to energy supply reliability has been investigated for defined divided electrical energy system during occurrence of a fault. The main reliability parameters of electrical equipment have been identified and calculated. Reliability of different small electrical energy system regimes has calculated and compared.**

***Index Terms*—Wind power, frequency, reliability.**

I. INTRODUCTION

Electrical energy system (EES) is a complex developing network of generators and customers. Since EES creation there have been energy reliability, energy quality and efficiency requirements for EES. Distribution reliability is one of the most important topics in the electric power industry due to its high impact on electricity cost and its high correlation with customer satisfaction. Currently developing electronic devices and information systems set high requirements for energy quality and especially for reliability with level of $1–1\cdot10^{-9}$ [1].

In large energy systems where power is transmitted 1000 km or longer distances systemic events increase which are called blackouts (eg.: USA (2003), Italy (2003), Brazil (2013)). Electricity supply lost in the country during the blackout is restored in just a few hours or even a day [2]. The large electrical energy system divided into small independently operated energy systems would ensure the supply of electricity, but for efficient division system has to be prepared for dividing. As shows Copenhagen - southern Sweden example of the systemic failure the active wind and traditional power plants were turned off. The electricity supply was started to the region through the sea cable from the wind power plant, which has been suspended.

Small electric energy system (SEES) concept is the system consisting of one or more generators and consumers which can be disconnected from EES and work autonomously for unidentified time period [3]. This system can be set up after the power system faults. Because the distribution system which contains generator would usually cut off and many consumers would stay without electricity [2].

In this paper SEES creation impact for energy supply reliability increment has been investigated. The main indexes of electrical equipments have been identified and the reliability parameters have been calculated. Reliability of different SEES regimes has been calculated and compared. Average energy losses of SEES and SEES divided into subsystems is calculated and compared.

II. WIND POWER PLANTS PECULIARITY OF RELIABILITY

The probability of wind power plant generation is the first characteristic which should be accounted. Wind power plants would not operate if there is no wind. Generally it is assumed that wind speed distribution corresponds to the Weibull law.

The second characteristic is inability of wind power plants to work independently. It is necessary that voltage and current frequency of electrical network were controlled and hold by other generating units capable to operate autonomously.

For calculation of power system operation reliability after disturbances of normal operation, it is necessary to estimate if the electrical links remains between the wind power plant and the main power plant. If any links are missed (e.g. short circuit fault in the interconnected line or disconnection of the main power plant), the wind power plant stops, disconnects from the electrical network and can be restarted only after intervention of operational staff.

Modern wind power plants are equipped with fault ride through capability which allows ignoring short term disturbances and frequency decreases in the network. Since fault duration is probabilistic value, generation of wind power plant is also probabilistic.

The voltage variation caused by remote short circuit fault is estimated. Variation magnitude depends on the distance to the short circuit fault spot and the duration depends on operation of protection devices.

Requirements for wind power plant operation during short circuit fault in electrical network according to the voltage are presented in Fig. 1 [4], [5].

Behaviour of generating plant provides dynamic grid support during grid faults by different behaviour sectors (Fig. 1):

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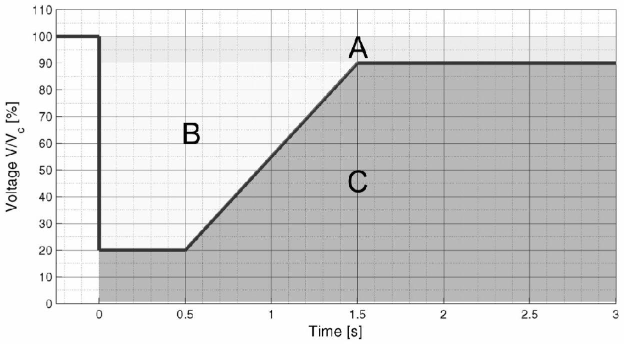

Fig. 1. Fault-Ride-Through curve and voltage at point common coupling.

- A: generating unit shall stay connected and operation within this area must not cause instability or separation from the public distribution;
- B: generating unit shall be able to run through without disconnecting and injection of short circuit current depends according to type of generating units or point of common coupling;
- C: no requirements and generating unit may disconnect. *Note:* These requirements are independent of the interface protection settings. Whether the generation plant will stay connected or not will also depend upon those settings.

Variation of active power of wind power plant at determined frequency conditions is presented in Fig. 2.

Possible frequency increase after load loss is evaluated. Governors of wind power plant should decrease output power. If frequency does not decrease, wind power plant should be disconnected. Disconnection is probabilistic function of load loss.

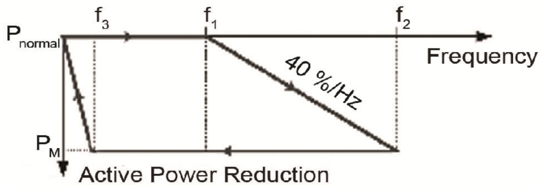

Fig. 2. Active power reduction for over frequency conditions.

Even if the generating unit does not contribute to power-frequency control it will need to reduce active power for grid frequencies equal or higher than f_1 = 50.2 Hz as presented in Fig. 2. When reaching 50.2 Hz actual active power injection is stated as P_M. Active power has to be reduced with a slope of 40 % per Hz. Active power may only be increased again when the grid frequency is lower than f_3 = 50.05 Hz. Disconnection of the generating unit at frequencies below f_2 = 52.0 Hz is not allowed. The insensitivity range of the frequency measurement shall be ±10 mHz or less

$$\Delta P = 20 P_{\mathrm{M}} \frac{50.2 - f_{\mathrm{grid}}}{50}, \qquad (1)$$

where P_M is actual power; f_{grid} is grid frequency [5].

Average generated power of wind power plants depends on three probabilities [6], [7]

$$P_{\mathrm{WPPa}} = P_{\mathrm{r}} \times p_{\mathrm{weibull}} \times p_{\mathrm{volt.}} \times p_{\mathrm{freq}}, \qquad (2)$$

where P_r is rated power; $p_{weibull}$ is probability of Weibull; $p_{volt.}$ is probability of voltage; $p_{freq.}$ is probability of frequency [8].

III. SMALL ELECTRICAL ENERGY SYSTEM EQUIPMENT RELIABILITY ASSESSMENT

Nowadays commercial wind power stations (WPS) show very high availability levels. Frequent maintenance and quick service determines actual WPS availability levels of 98 % or higher. WPS connected to wind power park (WPP) has lower determination to overall system reliability [9].

Equipment reliability is assessed by Frequency of Failure (FOF) without taking into account repair time. Therefore in further system calculations will be used Mean Time to Repair (MTTR) Scheduled Maintenance Frequency (SMF) and Mean Time to Maintain (MTTM).

All of the above mentioned reliability parameters are important. However FOF is most known parameter because of its unique characteristics and essentiality for all types of reliability analysis. FOF characterize individual properties of components. The general formula for assessing the FOF of component is

$$\mathrm{FOF}_i = \frac{\sum_{j=1}^{NN} NN_{ij}}{NN \cdot M_i \cdot T^{\Sigma}}, \qquad (3)$$

where NN is the number of failures of a component during interval [0, T]; NN_{ij} is the number of failures of the i-th component of the j-th equipment (i.e. WPS); M_i is the number of similar components in equipment or group of equipments; T^{Σ} is the total operational time of equipment.

MTTR represents the expected time to take for a failure to be repaired. General formula for MTTR is

$$\mathrm{MTTR}_i = \frac{T_r^{\Sigma}}{N_{\mathrm{r}i}}, \qquad (4)$$

where T_r^{Σ} is total repair time; N_{ri} is total repair time. SMP represents the frequency of scheduled maintenance period for equipment per year and is expressed by formula

$$\mathrm{SMP}_i = \frac{T^{\Sigma}}{N_{\mathrm{m}i}}, \qquad (5)$$

where N_{mi} is total scheduled maintenance number per equipment total operational time.

MTTM represents the average amount of time to perform scheduled maintenance on equipment. MTTM general formula is

$$\mathrm{MTTM}_i = \frac{T_{\mathrm{mr}}^{\Sigma}}{N_{\mathrm{m}i}}, \qquad (6)$$

where T_{mr}^{Σ} total maintenance repair time.

Mažeikiai power plant reliability is set as (1) in further calculations. Other average annual FOF, MTTR, SMF and

MTTM parameters of SEES equipments are taken from (4).

IV. Indexes for Reliability Assessment

The mostly used reliability indexes are averages that weight each customer equally. In these calculations small residential customer has just as much importance as a large industrial customer. Formulas for customer based indexes including System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), Average Service Availability Index (ASAI) and Energy Not Delivered (END) is given below [5]:

$$\text{SAIFI}=\frac{\sum f_i N_i}{\sum N_i}, \quad (7)$$

$$\text{SAIDI}=\frac{\sum T_{ai} N_i}{\sum N_i}, \quad (8)$$

$$\text{CAIDI}=\frac{\sum T_{ai} N_i}{\sum f_i N_i}, \quad (9)$$

$$\text{END}=\sum A_i f_i T_{ai}, \quad (10)$$

$$\text{ASAI}=\frac{\sum N_i \cdot 8760 - \sum T_{ai} N_i}{\sum N_i \cdot 8760}, \quad (11)$$

where f_i is frequency of interruptions; N_i is number of customers; T_{ai} is average interruption time; A_i is customer average load in formulas

Reliability indexes calculation is performed for SEES and divided SEES. Calculations are performed assuming that both systems are operating as normal energy systems. Obtained results are used for system reliability comparison.

Seeking to determine actual change of reliability, ASAI indexes are used as system reliability indexes and overall system reliability under SEES and divided SEES is defined by

$$R=1-\prod_{i}^{n} \overline{P}_i, \quad (12)$$

where $\overline{P}_i$ is unreliability of system; n is number of studied systems.

V. Architecture of Small Electrical Energy System

SEES location in Lithuania EES is given in Fig. 3. There are essential customers such as Mažeikių nafta, Klaipėda port, Būtingė oil terminal and 7 substations in SEES [1].

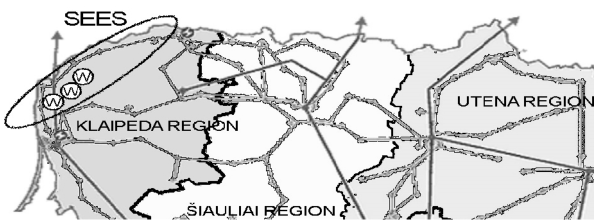

Fig. 3. Lithuania EES with SEES.

Architecture SEES is situated in Klaipėda region with leading Mažeikiai power plant connected to the 110 kV network and consisting of two 100 MW generators limited to 80 MW by turbine. Vėjas1 wind power park (WPP) rated generation is 30 MW with additional 28 MW shadow power station (SPS) generation. SPS must be connected close to the WPP [10]. Benaičiai and Sūdėnai WPP rated generation is 16.5 MW and 14 MW respectively with additional 28 MW SPS generation. Total capacity of wind power parks is 60.5 MW and total SPS generation is 56 MW.

Total customer power consumption is 99.25 MW. Consumption values used in calculations are measured during winter period when power consumption is highest. Power consumption of overall customer is 99.25 MW.

SEES system power balance is sufficient. SEES power generation exceeds power consumption. Power factor is not accounted in further calculations.

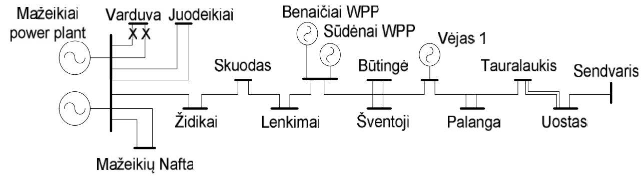

Fig. 4. SEES simplified scheme.

SEES reliability calculations have been performed for given simplified scheme in Fig. 4.

However it is possible that SEES might divide into 3 subsystems – areas (AREA 1, 2, 3) Fig. 5. Divided SEES with WPP must contain SPS, which ensures the required operating parameters for SEES. Division of SEES is based by assumption that WPP operates with leading SPS consisting of four 7 MW diesel generators with overall generation nearly equal to WPP rated generation. SEES aerial division should be performed only at short faulty periods when fault occurs in line or line segment. SEES division schemes might be different from presented but calculation and average results are similar.

Divided SEES reliability calculations have been performed for given simplified scheme in Fig. 5.

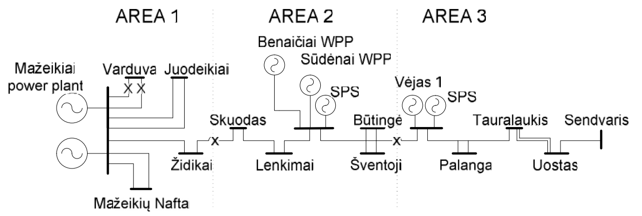

Fig. 5. Simplified scheme of SEES division.

VI. SEES Reliability Calculation Results

SEES and divided SEES SAIDI of individual customers is presented in Fig. 6. Especially high values are of divided SEES, area 2 where are Skuodas, Lenkimai, Šventoji and Būtingė customers with 2 WPP and SPS. Area 2 and 3 indexes are high because of relatively high WPP and SPS FOF indexes while Mažeikiai power plant index is very low.

SEES and divided SEES ASAI indexes for individual customer is presented in Fig. 7. Divided SEES values are lower especially in area 2. As mentioned above major factors are WPP and SPS FOF indexes.

Energy Not Delivered for each customer is presented in

Fig. 8. Values of divided SEES area 2 and 3 and SEES are comparable. Values of divided SEES are slightly higher in area 2, 3 than SEES. However overall END values of SEES and divided SEES are similar.

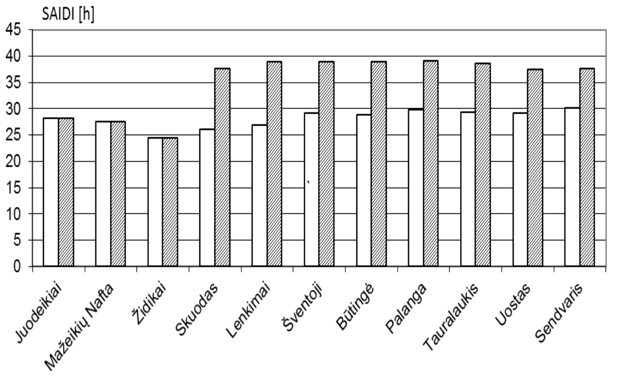

Fig. 6. SAIDI for individual customer in SEES and divided SEES (hours).

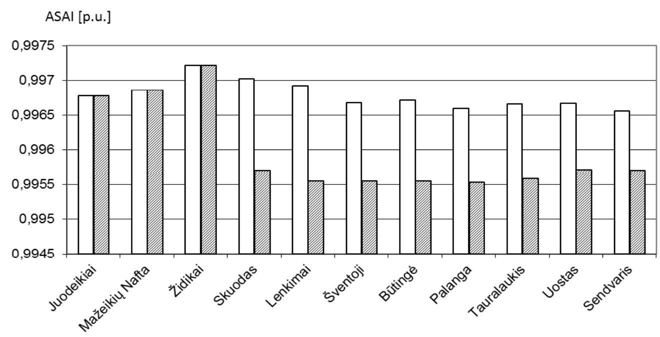

Fig. 7. ASAI for individual customer in SEES and divided SEES.

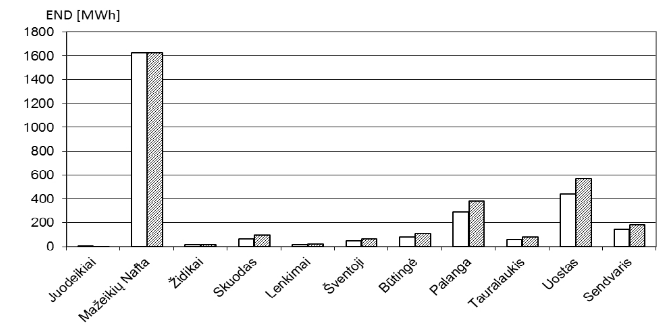

Fig. 8. END for individual customers in SEES and divided SEES.

Overall SAIFI, SAIDI, CAIDI, ASAI, END reliability indexes for SEES and divided SEES areas 1, 2, 3 are given in Table I.

TABLE I. INDEXES FOR SEES AND DIVIDED SEES.

Index	SEES	Divided SEES			
		Area 1	Area 2	Area 3	Average
SAIFI (times/year)	9.110	4.158	42.872	44.845	33.031
SAIDI (hours/year)	28.15	26.732	38.665	38.269	35.267
CAIDI (hours)	3.090	6.429	0.902	0.853	1.068
ASAI (p.u.)	0.997	0.997	0.996	0.996	0.996
END (GWh)	2.798	1.649	1.209	0.294	3.152

Divided SEES's SAIFI is greater than SEES because SEES leading power plant is Mažeikiai power plant while divided SEES leading plants are WPPs and SPSs. Average SAIFI of divided SEES would be 33.031 if WPP and SPS FOF are eliminated. However SPS's FOF, MTTR, SMP and MTTM indexes are significant and must be evaluated while WPPs and SPSs are leading power plants.

With EES reliability of 0.999, overall SEES energy supply reliability is $1\text{-}3.215\cdot10^{-6}$ and divided SEES average energy supply reliability is $1\text{-}1.294\cdot10^{-8}$. SEES energy supply reliability with ability to divide into areas nearly reaches required level $1\text{-}1\cdot10^{-9}$ of reliability.

VII. CONCLUSIONS

EES and SEES flexibility increases EES reliability and reliable and uninterrupted energy supply to customers during fault period.

END is 2.798 GWh loss of energy annually in SEES while END is 3.152 GWh loss of energy in divided SEES.

SEES and divided SEES ASAI indexes are similar but divided SEES is more unreliable because of WPP and SPS reliability, yet SEES and divided SEES blackout possibility during EES fault period becomes almost impossible.

EES division to smaller systems determines average service reliability index increment from 0.999 to $1\text{-}3.215\cdot10^{-6}$ and further SEES division determines $1\text{-}1.294\cdot10^{-8}$ average reliability.

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