Feasibility assessment of variable-speed generator set concepts with focus on rating of power electronic equipment

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Abstract

Four different engine-generator concepts with variable-speed operation of the internal combustion engine are analyzed regarding relevant performance criteria. The topologies under investigation have an internal energy storage in order to mitigate the impact of load steps. The performance criteria address the required rating of the power converters in stationary operation, after load steps and to deliver short-circuit current.

Introduction

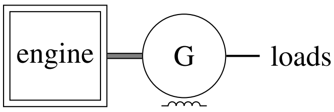
Mobile generator sets are mainly used for the supply of electrical power in off-grid applications, e.g. at construction sites, as well as for grid support parallel to weak grid access points. Furthermore, they are used for emergency power supply.

The state-of-the-art solution consists of a Diesel engine coupled to a synchronous generator running at constant speed, as depicted in Fig. 1a. In practical applications, where the generator set has to supply loads with a high starting current, e.g. asynchronous machines, or nonlinear loads, e.g. diode rectifiers, the rated power of the generator set is chosen up to three times the rated power of the loads [1, 2]. This setup has been proven to be very robust and reliable, however large and not energy-efficient:

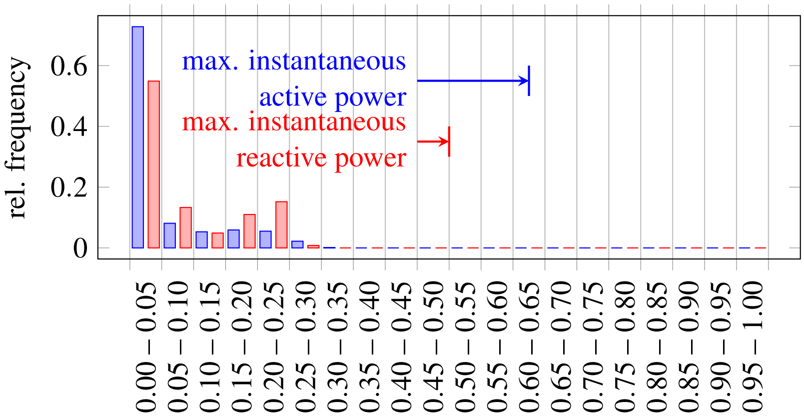
- Since the generator set is designed for the peak power, most of the time it runs only at part load, typically below 20% of the rated power. In order to illustrate this, Fig. 1b shows the histogram of the power demanded from a generator set in a typical application from a construction site. Such a load profile implies that the Diesel engine consumes more fuel for the same amount of electrical energy compared to an operation in the engine map range of optimal fuel consumption. This range is located typically at approximately half the rated engine speed and 70% to 80% load. The engine can also be designed specifically for lowest fuel consumption in a particular map range, but this is always also a function of the desired rated power.
- Since the speed of the generator set is proportional to the grid frequency, it is neither possible to run the engine at higher nor at lower speeds. Higher speeds may be beneficial in order to gain more power from the same engine, lower speeds may help to reduce fuel consumption at lower loads.

This motivates to investigate alternative concepts. Similar as in wind energy conversion systems, there are two main concepts that have been proposed [3]:

- First of which uses a synchronous machine running at variable speed which is connected to a back-to-back converter. The DC link can optionally be supported by an energy storage [4]. In low-power



(a) Conventional generator set



(b) Histogram of loading

Fig. 1: Block diagram of the conventional fixed speed concept (a) and histogram (b) of the loading of such a genset with a rated power of 500 kVA (400 kW active power) in a crane application: the data is taken from 3-minute-average measurements of active power (blue) and reactive power (red). The abscissa shows the relative loading referring to the rated active power.

applications, the machine side front end can be realized by a simple diode rectifier with a boost converter as in [4, 5]. Otherwise, an active front-end is proposed [6]. The concept is also attractive for full or hybrid ship propulsion systems [7, 8].

- The second concept employs a doubly-fed induction generator (DFIG) as in [9, 10]. In this concept, a partial power rating of the power electronics converters is intended. Here as well, the DC link may be equipped with an energy storage.

Both concepts are gearless and increase the efficiency especially when operated at partial load. A further configuration employs an electric Continuously Variable Transmission (e-CVT) which is a special gear box with three mechanical ports. In [11, 12], it has been proposed for ship propulsion systems. Although being applicable for the present system as well, it is considered to be out of scope here in order to stay with a gearless solution.

Crucial for an industrial application is the rating of the power converters because they are considered to be the most expensive part. For low-power applications, selectivity in the protection system may not be required. This means that a short circuit may shut down the whole system. However, in applications for higher power or emergency supplies this is not acceptable and the power system must be able to sustain the short circuit current in order to trigger the protection devices, e.g. fuses. This is the weak point of both concepts: For the fully-rated conversion, the grid-side converter (GC) must be rated to more than rated current. In case of the DFIG with partially rated power converters, the control of the system via the machine-side converter (MC) is lost during the fault due to the clamping action of the crow-bar circuit [13, 14] that protects the MC from overvoltage.

This is why, another solution is proposed that preserves a synchronous machine directly coupled to the grid. Thus, short-circuit currents can be delivered without stressing the power electronics converters with this task. In order to adapt the speed of the internal combustion engine (ICE) to the fixed speed of the synchronous machine, a cascaded machine (CM) with two rotors as in [15] is inserted between both components, see Fig. 2. It exposes three energy ports: the two rotating shafts both of which carry the same torque at different speeds (except for the accelerating and frictional torque) and an electrical port accessible via three-phase slip rings which provide the slip power to a power electronic converter.

In order to be able to withstand load steps, in particular when the ICE is running at low speed and needs to be accelerated before being able to take over the full load, an energy storage is required. This can be realized as an electrical one connected to the DC link or a flywheel and allows for a set of combinations. The essential ones are presented below. The goal of the present paper is to evaluate the concepts in terms of efficiency and the power rating of the ICE, the electrical machines and the power converters. For this

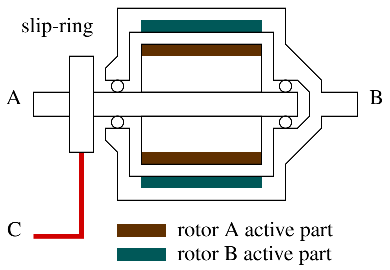


Fig. 2: Principle diagram of a cascaded machine, depicted without outer housing. The construction allows independent rotational speeds at the shaft ends A and B whose interacting torque is controlled by the three-phase electric machine that is formed by the active parts at both sides of the air gap. The speed difference and the interacting torque determine the corresponding electric power that is exchanged via the slip-ring system at the connection C. For a considerable operating range, the electric power is smaller than the mechanical power, offering the benefit of a partial power converter.

investigation, a power plant in the medium power range is considered.

The paper is organized as follows: In the next section, the requirements and performance criteria are discussed. This is followed by a section describing the concepts investigated before a comparison is done in a further section. The last section gives a conclusion.

Requirements and performance criteria

Focusing on stand-alone applications in the medium to high power range (30 kVA to 500 kVA rated power), one single generator set has to supply multiple electrical devices. This implies the following:

- The grid provided by the generator set has to supply the (possibly stepwise changing) load, which is one of the main reasons for the overdimensioning according to the state-of-the-art.
- The protection system of the grid must provide selectivity, i.e. a short circuit must trigger only the corresponding breaking element in order to minimize the number of loads affected. Therefore, the system must be capable of supplying a sufficiently large current for a few seconds.
- The efficiency of the whole system should be as high as possible.
- Targeting cost-effective mobile applications, the total weight and the rating of the power components must be as low as possible.

In view of the above expectations, potential variable speed concepts should combine the individual strengths of each system component and aim at a mutual compensation of possible weaknesses. Here, the following comparison criteria are used:

- Sizing of the grid facing components considering the short circuit current requirement.
- Power flow sharing among the components in stationary operation.
- Power flow sharing among the components after load steps.

Since the considered power range can be handled with a low-voltage solution, the power electronic converters will be of the two-level or three-level voltage source converter type, because these topologies are expected to provide the most economic solution. Moreover, these topologies allow a straight-forward extension from three phases to four phases to allow feeding of single phase loads via the GC.

Engine-generator concepts

Concept A: Fully-rated conversion A straight-forward concept for variable speed operation is given by the block diagram in Fig. 3a. The conventional concept is extended by a MC and a GC operating in a back-to-back configuration in order to unlink the engine speed from the grid frequency. The energy storage, e.g. a super capacitor or battery, is connected to the DC link.

Each energy conversion stage must provide full system power capacity. In principle, a diode rectifier suffices as the MC. However, an active rectifier is assumed in the following, since it does not limit the choice of the generator type, can boost the generator voltage and allows motor-operation to quickly accelerate the ICE to the new operating point after load steps. For large load steps, the generator accelerates the ICE with the help of the energy storage which also takes over the load via the GC. Both converters will have a considerable cost footprint since each must handle the full power while the GC must even be rated for the short circuit current, which is the main drawback of this concept. The advantages are a low

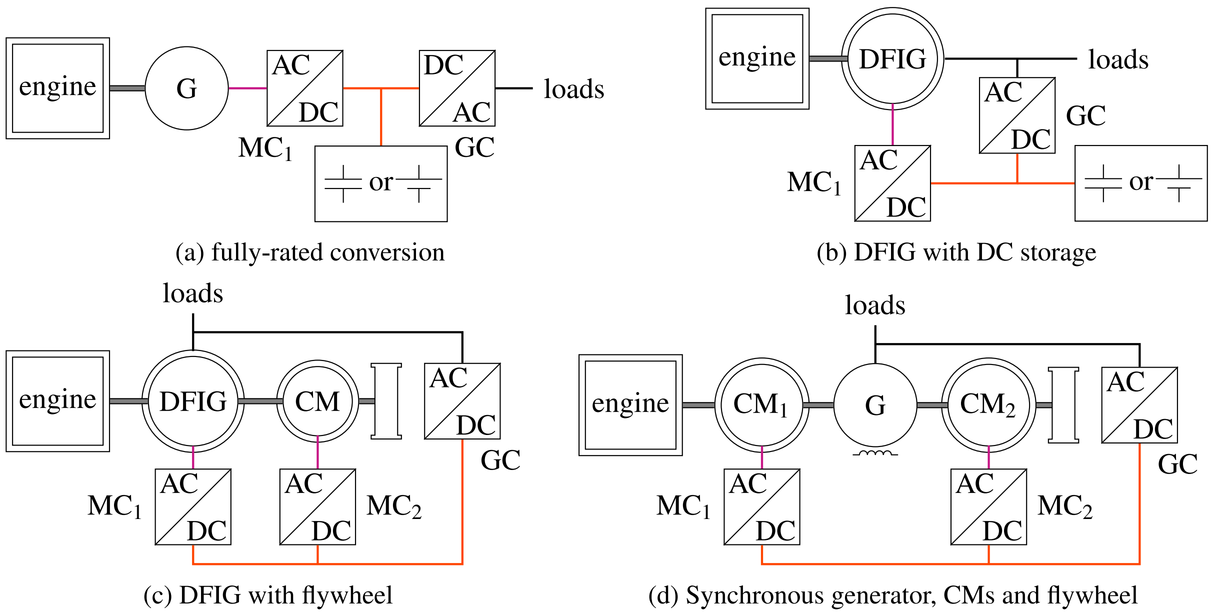


Fig. 3: Block diagrams of variable speed concepts: (a) fully-rated conversion allowing various generator types; (b) and (c) partial power conversion based on a DFIG; (d) partial power conversion based on a CM and synchronous generator. Concepts (a) and (b) use a super-capacitor- or battery-based storage connected to the DC link, while concepts (c) and (d) use a flywheel-based storage, coupled to the shaft.

number of main components, a simple mechanical system, and more design freedom for the optimization of the generator, since it is decoupled from the grid such that the respective requirements do not apply anymore.

Concept B: Doubly-fed induction generator with DC storage DFIGs offer two parallel paths for the energy flow, allowing a partial power rating of both, the machine and the power electronic conversion stages in a useful speed range. The block diagram is depicted in Fig. 3b. During high-load operation, the shaft speed is higher than synchronous speed and the slip power is transmitted via the MC and GC to the load. During low-load operation, the shaft speed is lower than synchronous speed while the corresponding slip power is fed into the rotor implying a circular energy flow involving the DFIG and both converters. Although the DFIG can help to relieve the GC from a large part of the short circuit current, the control of the system is impaired during grid faults, because of the crow-bar operation in the rotor circuit. Matching the MC and the standstill voltage of the DFIG in order to spare protective measures during grid faults is unfeasible because it impedes the partial power rating. Similar to the fully-rated conversion, the energy storage is connected to the DC link of the converters.

Concept C: Doubly-fed induction generator with flywheel A flywheel is used in order to avoid motor operation of the DFIG during load steps with the aim to reduce the power requirements of the GC. This is depicted in the block diagram in Fig. 3c. In order to control the torque and the speed range of the flywheel, a CM is used. During stationary operation, the flywheel maintains a higher speed than the main shaft. During a load step, the flywheel momentum is released to accelerate the ICE via the shaft and to supply the load via the DFIG. Moreover, a part of the momentum is extracted as electric power via the slip rings and provided to the DC link to be used by the MC or GC. Since a large part of the flywheels momentum is transferred as mechanical power, the respective power electronics converter only handles a fraction of that.

Compared to the previous concept, the GC can be smaller, however, this concept faces the same challenges during grid faults: control of the system is severely restricted due to the crow-bar operation.

Concept D: Synchronous generator with electromechanical transmission with flywheel In order to increase the short circuit current capability while maintaining full system control during faults, this concept employs a DC excited synchronous generator to take over the major part of the load during normal operation and to provide the short circuit current during faults. The block diagram is depicted in Fig. 3d. Variable speed operation is achieved by CM_1 and the energy storage is based on a flywheel, coupled via CM_2 to the main shaft, as in the previous concept.

In this concept, partial power rating for the converters and the synchronous generator is maintained during all relevant modes of operation. For high-load condition, the speed of the ICE is higher than the main shaft speed and the slip power of CM_1 is provided via the power electronics converters to the load, implying power sharing between the machines and the converters. During a load step, the flywheel feeds the load via the generator and the GC while it also accelerates the ICE via both CMs. Since the energy flow uses parallel electrical and mechanical paths during stationary and dynamic operation, this arrangement enables partial power rating for both, power converters and electric machines. Its main drawback is the increased number of main components. However, the rated power of each conversion stage is lower than the full system power.

Comparison

Sizing of the grid facing components considering the short circuit current requirement

In order to design a selective protection scheme, a three-phase short circuit current of three times the full load current for several seconds can typically be expected from a conventional generator set [16]. Assuming the same for the variable-speed systems, the GC of Concept A must be rated to three times the generator power, because the short circuit duration is much longer than the semiconductor thermal time constants, implying stationary operation of the converter. In the DFIG-based Concepts B and C, the electric machine and the GC contribute to the short circuit current, raising the hope of a reduced GC rating if the control challenges are solved that arise from the crow-bar operation during the fault. Compared to the other concepts, the lowest short circuit current requirement can be expected for the GC of Concept D, since the synchronous generator is able to reliably provide the majority of fault current by leveraging its thermal overload capability.

Power flow sharing among the components in stationary operation

In order to compare the power flow for each of the concepts, a minimum set of assumptions has to be made. Here, an application with a grid frequency of 50 Hz is assumed. The electrical machines have four poles which leads to a synchronous speed of $n_{\text{sync}} = 1500\,\text{rpm}$. The speed of the ICE is $n_E \in [\check{n}_E, \hat{n}_E]$, with $\check{n}_E = 1000\,\text{rpm}$ and $\hat{n}_E = 3000\,\text{rpm}$, where the lower or upper end is used when the power demand is low or high, respectively. The efficiency of the power conversion stages in a steady-state operation is denoted as $\eta_E = 0.4$, $\eta_G = \eta_{\text{CM}} = \eta_C = 0.95$ for the ICE, the generator, the CM and the power electronics converters, respectively. These values are assumed to be realistic for industrial applications above 30 kVA.

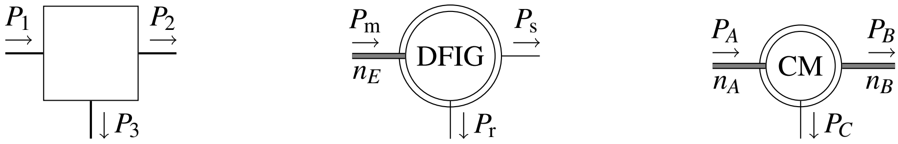
The DFIG and the CM are modeled as three-port devices as depicted in Fig. 4a including the direction definitions of the port powers P_1, P_2, and P_3. When P_1 is positive in stationary operation, the relation

$$P_1 \eta = P_2 + P_3 \tag{1}$$

is used to consider an energy conversion efficiency $0 < \eta \leq 1$. The port powers of the DFIG and the CM are defined in Figs. 4b and 4c, respectively and they correspond to the powers in (1) as given by Table I. The slip of the DFIG and the CM are denoted by s and s_{CM}, respectively, and their definitions read

$$s = \frac{n_{\text{sync}} - n_E}{n_{\text{sync}}}, \qquad s_{\text{CM}} = \frac{n_B - n_A}{n_B}, \tag{2}$$

with the mechanical speeds n_A, n_B of the CM. In a similar manner, the stationary operation of the power electronics converters, the ICE, and the synchronous generator can be modeled with their respective port



(a) general (b) DFIG (c) CM

Fig. 4: Three-port representations: general (a); DFIG (b); CM (c). The power relations are given by (1) after inserting the corresponding definitions from Table I.

Table I: Port power and efficiency definitions for the component modeling with (1). The general three-port system with the power directions are indicated in Fig. 4a. The slip of the DFIG and the CM are given by (2). In case of non-ideal conversion, i.e. $\eta < 1$, the models are valid for $P_1 > 0$.

	general	DFIG	CM	ICE	MC	GC	generator
power at port 1	P_1	P_m	P_A	P_{fuel}	$P_{MC,AC}$	$P_{GC,DC}$	$P_{gen,m}$
power at port 2	P_2	P_s	P_B	$P_{E,m}$	$P_{MC,DC}$	$P_{GC,AC}$	$P_{gen,s}$
power at port 3	P_3	$P_r = -sP_s$	$P_C = -s_{CM}P_B$	0	0	0	0
efficiency	η	η_G	η_{CM}	η_E	η_C	η_C	η_G

powers and conversion efficiencies, as indicated in the other columns of Table I. The third port power is not needed in these cases, since they are two-port devices, i.e. $P_3 = 0$.

In the following analysis, constant conversion efficiencies have been assumed for the components and their dependency on the DFIG- or CM-slip is neglected. In order to obtain a mathematical representation of each concept, the respective block diagrams can be translated to equations in the port powers from Table I. This results in

$$P_{load} = P_{GC,AC} \qquad P_{GC,DC} = P_{MC_1,DC} \qquad P_{MC_1,AC} = P_{gen,s} \qquad P_{gen,m} = P_{E,m} \tag{3}$$

for Concept A,

$$P_{load} = P_{GC,AC} + P_s \qquad P_{GC,DC} = P_{MC_1,DC} \qquad P_{MC_1,AC} = P_r \qquad P_m = P_{E,m} \tag{4}$$

for Concepts B and C, and

$$P_{load} = P_{GC,AC} + P_{gen,s} \qquad P_{gen,m} = P_B \qquad P_{GC,DC} = P_{MC_1,DC} \qquad P_{MC_1,AC} = P_C \qquad P_A = P_{E,m} \tag{5}$$

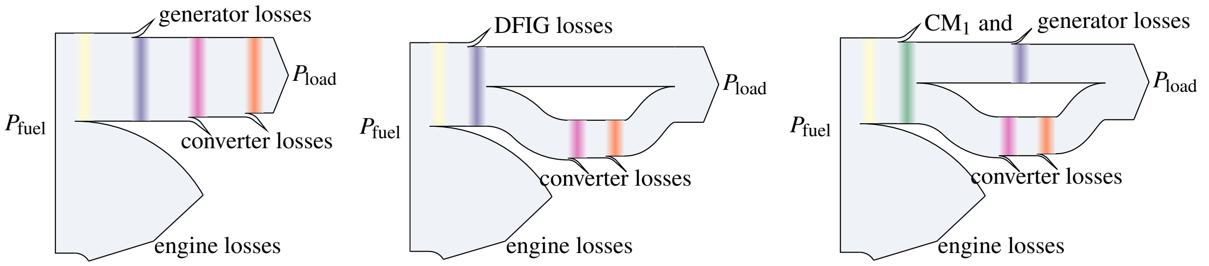
for Concept D. During stationary operation at high load, the ICE runs at $\hat{n}_E$, implying operation above synchronous speed for the DFIG- or CM-based concepts B, C, and D. For this mode of operation, the models in Table I are valid and the required fuel power P_{fuel} for a given load P_{load} can be determined by successive elimination and substitution of the relations in (3), (4), and (5) for Concept A, the Concepts B and C, and Concept D, respectively, until only P_{load} and P_{fuel} remain. This can be achieved by applying the general model (1) with the definitions from Table I and results in

$$P_{fuel} = P_{load}\left(\eta_E \eta_G \eta_C^2\right)^{-1} = 2.92\,P_{load} \quad \text{for Concept A} \tag{6}$$

$$P_{fuel} = P_{load}\,(1-\hat{s})\left(\eta_E \eta_G \left(1-\hat{s}\eta_C^2\right)\right)^{-1} = 2.77\,P_{load} \quad \text{for Concepts B, C} \tag{7}$$

$$P_{fuel} = P_{load}\,(1-\hat{s}_{CM_1})\left(\eta_E \eta_{CM} \eta_G \left(1-\hat{s}_{CM_1}\eta_C^2\right)\right)^{-1} = 2.84\,P_{load} \quad \text{for Concept D} \tag{8}$$

with the slip $\hat{s} = \hat{s}_{CM_1} = \frac{n_{sync} - \hat{n}_E}{n_{sync}}$. From the intermediate expressions, the port powers of each component can be obtained leading to the Sankey diagrams in Fig. 5 that depict the corresponding energy flow for the Concepts A to D. As a common basis for comparison, the load power P_{load} is the same in each diagram.



(a) Concept A (b) Concepts B and C (c) Concept D

Fig. 5: Sankey diagrams for the Concepts A to D during stationary operation for high-load, implying operation above synchronous speed for the DFIG or CM. The load is the same for each diagram in order to visually compare the power carried by each component. The output power of the respective component is indicated by color: ICE, generator or DFIG, CM_1, GC, MC_1.

The relevant power for the rating of the respective power electronics converters are given by

$$P_{\text{GC,AC}} = P_{\text{load}} \qquad P_{\text{MC}_1,\text{DC}} = P_{\text{load}}/\eta_C \qquad \text{for Concept A} \tag{9}$$

$$P_{\text{GC,AC}} = P_{\text{load}}\hat{s}/(\hat{s}-\eta_C^{-2}) \qquad P_{\text{MC}_1,\text{DC}} = P_{\text{load}}\hat{s}/(\eta_C\hat{s}-\eta_C^{-1}) \qquad \text{for Concepts B, C} \tag{10}$$

$$P_{\text{GC,AC}} = P_{\text{load}}/(1-\eta_G\eta_C^{-2}\hat{s}_{\text{CM}_1}^{-1}) \qquad P_{\text{MC}_1,\text{DC}} = P_{\text{load}}/(\eta_C-\eta_G\eta_C^{-1}\hat{s}_{\text{CM}_1}^{-1}) \qquad \text{for Concept D.} \tag{11}$$

Compared to the fully-rated Concept A, the converter powers of the other concepts are smaller, since the DFIG of Concepts B and C or the CM_1 of Concept D allow a fractional rating of the power converters.

Power flow sharing among the components at the start of load adaptation

As outlined above, the generator set must be able to deal with large load changes. In order to keep the energy storage small, the ICE must change operating points quickly which means that it may need to be accelerated. The worst-case scenario applies directly after a large load step during a low-load condition, i.e. where the internal combustion engine needs to be accelerated from low to required engine speed before it is able to take over the load. For the sake of simplicity, the contribution of the combustion process to the acceleration is neglected, leaving the respective energy storage as the sole source. Since the focus lies on the distribution of the power between the components, the losses are neglected because their impact is considered to be low. Thus, the power flow sharing at the start of load adaptation can be obtained with the modeling scheme from the previous section as well, since the models become valid for a potentially reverse power flow. In this case, the dc storage for concepts A, B and the flywheel for concepts C, D need to be considered, since they provide the energy. With P_{load} and P_{acc} being the load power after the load step and the power dedicated to the acceleration of the ICE, the powers relevant for the rating of the respective power electronics converters are:

$$P_{\text{GC,AC}} = P_{\text{load}} \qquad P_{\text{MC}_1,\text{AC}} = P_{\text{acc}} \qquad \text{for Concept A} \tag{12}$$

$$P_{\text{GC,AC}} = P_{\text{acc}}/(1-\check{s})+P_{\text{load}} \qquad P_{\text{MC}_1,\text{DC}} = P_{\text{acc}}\check{s}/(1-\check{s}) \qquad \text{for Concept B,} \tag{13}$$

where $\check{s} = \frac{n_{\text{sync}}-\check{n}_E}{n_{\text{sync}}}$ denotes the slip at the start of load adaptation. For the flywheel-based concepts, the powers depend on the slips $\hat{s}_{\text{CM}} = \frac{\hat{n}_{\text{FW}}-\check{n}_E}{\hat{n}_{\text{FW}}}$, $\check{s}_{\text{CM}_1} = \frac{n_{\text{sync}}-\check{n}_E}{n_{\text{sync}}}$, and $\hat{s}_{\text{CM}_2} = \frac{\hat{n}_{\text{FW}}-n_{\text{sync}}}{\hat{n}_{\text{FW}}}$ of the CMs, leading to

$$P_{\text{GC,AC}} = P_{\text{MC}_2,\text{DC}} + P_{\text{MC}_1,\text{DC}} \tag{14}$$

$$P_{\text{MC}_1,\text{DC}} = \check{s}\left[P_{\text{acc}}\hat{s}_{\text{CM}} + P_{\text{load}}(\hat{s}_{\text{CM}}-1)\right](1-\check{s})^{-1} \tag{15}$$

$$P_{\text{MC}_2,\text{DC}} = (P_{\text{load}}+P_{\text{acc}})\hat{s}_{\text{CM}} \tag{16}$$

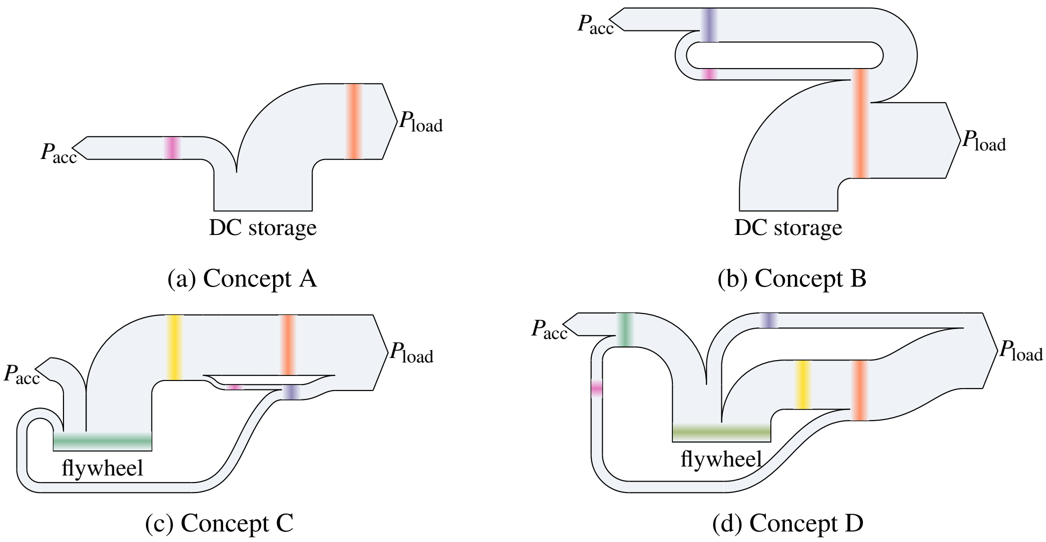


Fig. 6: Sankey diagrams for the Concepts A to D at the instant after a large load step during low-load condition, implying operation below synchronous speed for the DFIG and CM. The load P_{load} is the same for each diagram as well as the accelerating power P_{acc} that is used to quickly reach the new operating point of the ICE. The power of the respective component is indicated by color: ■ GC, ■ MC_1, ■ MC_2, ■ generator or DFIG, ■ CM or CM_1, ■ CM_2.

for Concept C, and for Concept D to

$$P_{GC,AC} = P_{MC_1,DC} + P_{MC_2,DC} \tag{17}$$

$$P_{MC_1,DC} = -P_{acc}\check{s}_{CM_1}(\check{s}_{CM_1} - 1)^{-1} \tag{18}$$

$$P_{MC_2,DC} = (P_{load} + P_{acc})\hat{s}_{CM_2}. \tag{19}$$

Similar as above, the Sankey diagrams in Fig. 6 illustrate the power flow and the required rating of the converters. In each diagram, the load P_{load} and the accelerating power $P_{acc} = 0.3P_{load}$ are the same, relying on the DC storage for the Concepts A and B or on the flywheel for the Concepts C and D. For all concepts, the speed of the engine is assumed to be at its lower end $\check{n}_E$ and for Concepts C and D, the flywheel is running at its upper speed range end $\hat{n}_{FW} = 3000\,\text{rpm}$. Similar as in Fig. 5 for the stationary operation, the required power capability of the power electronics and the electric machines can be compared for this key operating condition. The GC of Concept A continues to carry the full system power, while the MC acts as inverter, carrying the accelerating power and the generator losses since the latter runs in motor operation, as shown in Fig. 6a. The GC of Concept B handles even larger power than the GC of the fully-rated concept, because it takes over the full load plus the accelerating power and even the rotor power which the DFIG requires, since it runs below synchronous speed. Consequently, the Concept B is unsuitable for accelerating the internal combustion engine, since the energy storage connection at the DC link implies a suboptimal energy flow. The flywheel-based Concepts C and D do not suffer from this problem and thus, are better suited for accelerating the ICE, as visible from Figs. 6c and 6d. The flywheel-provided powers in Concepts C and D are similar to the battery or super-cap powers in Concepts A and B, however, the flywheel converter power in Concept C is larger than in Concept D, since the respective speed difference to the main shaft is larger. In contrast to Concept B, the rotor power of the DFIG in Concept C advantageously contributes to feeding the load, because the circular energy flow of Concept B is avoided in generator operation below synchronous speed. However, similar to Concept B, Concept C suffers from a problematic power flow pattern when the flywheel speed is lower than the main shaft speed while the latter is still lower than synchronous speed. This rotational speed constellation requires a power flow into both, the CM and the DFIG rotor, which must be provided via the DFIG stator and the GC. Avoiding this operation mode increases the system design effort and control challenges for Concept C. Concept D is better in this regard, since the speed difference of the flywheel

Table II: Comparison of the rating of the converters in relation to P_{load} for stationary and transient operation as well as for providing short circuit current. The values in the transient and stationary rows correspond to Figs. 5 and 6, respectively. For the transient case, the losses have been neglected. The maximum power determining the required rating is highlighted in boldface.

	Concept A		Concept B		Concept C			Concept D		
	GC	MC_1	GC	MC_1	GC	MC_1	MC_2	GC	MC_1	MC_2
stationary	1.00	**1.05**	0.47	**0.50**	0.47	**0.50**		0.48	**0.51**	
transient	1.00	0.30	**1.45**	0.15	**0.80**	0.06	**0.87**	**0.80**	0.15	**0.65**
short circuit	**3.00**									

to the main shaft decreases much slower during discharging operation than for Concept C, because the main shaft speed is maintained at synchronous speed.

Results

The quantitative results of the comparison are collected in Table II and can be summarized as follows:

Concept A has the lowest number of main components. In order to supply short-circuit current, the GC must be rated much higher than for nominal load. However, for acceleration of the ICE, the power flow of the MC is reversed but does not require a higher rating of the converter. Nevertheless, the required rating of the GC seems to be the largest drawback of the concept.

Concept B suffers from an inconvenient loading of the GC when it is necessary to accelerate the ICE. Thus, maintaining this feature demands a higher than nominal grid converter rating. However, together with Concept C, it seems to be the most efficient configuration in a stationary operation at full load.

Concept C avoids the main drawback of Concept B such that a partial-load rating of the GC can be achieved. However, as for Concept B, the controllability of the system is lost in case of short circuits.

Concept D avoids the main drawbacks of the other concepts with a slightly worse efficiency compared to Concepts B and C but a better efficiency than Concept A, making it highly attractive for further research.

Conclusion

Conventional fixed-speed generator sets suffer from low efficiency in case of highly variable load scenarios, such as e.g. construction sites, due to the long periods of low power operation and occasional peak load demand. Variable-speed operation of the ICE improves the conversion efficiency during low-load operation, allowing for an overall fuel saving compared to the conventional fixed-speed concept. The present paper compares different concepts of gearless generator sets that allow for a variable-speed operation of the ICE and feature an integrated energy storage to increase the resiliency with respect to load steps. Furthermore, since all configurations have a power electronic converter directly coupled to the grid, they are, in principle, capable of dealing with nonlinear loads. The paper compares four concepts two of which use an electrical storage while the other two use a flywheel. The investigations show that one of the concepts outperforms the other ones because it is the only one which satisfies the following key criteria: 1) the rating of the power electronics converters is below the rated power of the system, 2) it is possible to accelerate the ICE externally after a load step, 3) the system is able to deliver short-circuit current in order to trigger protection devices without losing the controllability. As a result, the paper adds one more promising concept to the set of variable-speed generator set configurations that have been investigated in recent research.

However, there remain open questions that have not been targeted yet. The dimensioning of the energy storage, the ability to supply reactive power as well as more detailed investigations on the efficiency obtained in a realistic scenario are left for future research.

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