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Zhe Chen[1,2], Jens Carsten Hansen[1,3], Qiuwei Wu[1,4], Anca Daniela Hansen[1,3], Birgitte Bak-Jensen[1,2]

[1]Wind Energy, Sino-Danish Centre for Education and Research (SDC)
[2]Department of Energy Technology, Aalborg University, Denmark
[3]Risø-DTU National Laboratory for Sustainable Energy, Technical University of Denmark, Denmark
[4]Centre for Electric Technology (CET), Technical University of Denmark, Denmark

Abstract

This paper presents an overview on the recent research activities and tendencies regarding grid integration of wind power in Denmark and some related European activities, including power electronics for enhancing wind power controllability, wind turbines and wind farms modeling, wind power variability and prediction, wind power plant ancillary services, grid connection and operation, Smart grids and demand side management under market functionality. The topics of the first group of PhD program starting 2011 under the wind energy Sino-Danish Centre for Education & Research (SDC) are also mentioned.

Keywords

Wind power research, power electronics, modeling, prediction, ancillary services, grid connection and operation, demand side management, electrical vehicles, electricity market, Sino-Danish Centre for Education & Research (SDC).

Wind power technology is the most competitive renewable energy technology today, and the sustainable development of power systems is expecting wind energy to make large contributions to the future power systems [1], [2]. The challenges of developing the technologies of wind turbines, wind farms and power systems in order to enable the integration of the increasing amounts of wind power in the coming decades are significant. Extensive research is needed to be able to deal with these challenges while maintaining reliability and security of power systems.

Denmark and a few other areas of European power systems already have wind energy penetration levels of more than 20% and aim at 30-50% in a not too distant future. Denmark may thus be viewed as a demonstration area for new technologies and solutions regarding integration of wind power.

Effective grid integration of wind power should enable wind energy to contribute as a backbone of future power systems. Active research is in progress to provide solutions so that the wind turbines can perform as modern generation units, in terms of control of frequency and voltage, and other grid operation requirements.

This paper presents an overview of the recent research activities and tendencies regarding grid integration of wind power in Denmark and some related European activities.

Power electronics-an enabling technology for wind turbine integration

Power electronic, being the technology of efficiently converting electric power, is an enabling technology in wind power systems [3-5]. It is an essential part for integrating the variable speed wind power generation units to achieve high efficiency and high performance. The wind turbine size is still increasing. 7 MW wind turbine is in operation and 10 MW wind turbine is being developed. Large scale integration of wind turbines may have significant impacts on the power quality and power system operation. The technical specifications, grid codes, for grid connection of wind turbines (the large offshore wind farms to high-voltage transmission networks as well as the local wind turbines to distribution networks) have been produced to specify the requirements that wind turbines and wind power plants must meet in order to be connected to the grid.

In new wind turbines, power electronic converters provide enlarged control capabilities to wind farms to fulfill the very stringent grid requirements imposed by transmission system operators (TSOs). They provide wind farms with power plant characteristics, such as control of active and reactive power, frequency, voltage and low voltage ride through (LVRT) capability, etc. Research on power electronic technology is very fast, covering different aspects, i.e. from material studies to reliable components and circuits, which can effectively support the development of power electronic applications in wind power industry.

Applications of power electronic based *FACTs* devices, such as *Static Synchronous Compensator* (*STATCOM*) and *Dynamic Voltage Restorer (DVR)*, have been studied in connection to large scale wind power application. In normal operation condition, the flexible AC transmission systems (*FACTS)* devices can supply reactive power to support the voltage control of the power system where the wind farms are connected. The reactive power can also be controlled to compensate for the flicker caused by active power fluctuation due to the wind speed variation [6]. During grid fault operation conditions the converter can support voltage recovery by quickly injecting reactive current [7-11].

The European commission has been promoting the use of renewable energy. In particular, offshore wind farms will become a development focus, as 68 GW offshore wind farm in the North Sea is expected before 2030 [12]. From this perspective, a super grid, namely an offshore transmission grid connecting the offshore wind farms and the power grids of the surrounding countries [13], could have an important role to transfer renewable energy among the countries and may significantly reduce power variability of renewable energy sources. The Voltage Source Converter (VSC) based HVDC transmission is favourable for super grid application. VSC-HVDC is a key technology to develop offshore super grid. The super grid is also seen as an opportunity to combine the production of a fluctuating renewable energy source (wind) with dispatchable sources of renewable energy such as hydro storage. The hydro power plants available in Norway could be thus used as storage when the wind power is excessive and as a backup power supply when the wind power is insufficient. Some possible configurations of offshore super grid in the North Sea have been proposed, one example is shown in Fig. 1.

Fig. 1. An example topology of offshore super-grid [14].

In future, the percentage of wind energy on many national grids or interconnected systems is expected to be significant, which is making wind turbines as key grid players. Nowadays, power system operators revise continuously the grid codes. They require wind turbines to have a built-in capability of acting like conventional power plants. Power electronic technologies, used as the interfaces for wind turbines and some energy storage systems, and in FACTS devices and HVDC systems, will play a significant role in developing new state-of-the-art solutions for the future success of wind power.

Ancillary services provided by wind power plants for support of power systems

Old traditional wind turbines are not required to participate in frequency and voltage control. However, in recent years, the attention has been drawn to wind farm’s ability to support power system operation. Consequently, many grid codes have been re-defined to specify the requirements that wind turbines and wind power plants must meet in order to be connected to the grid. Examples of such requirements include the capabilities of contributing to frequency and voltage control by continuously adjusting active power and reactive power contribution from wind turbines,. The reactive power and voltage control ability of wind turbines can be enhanced by the aforementioned power electronic application, while frequency response of wind turbines is more related to the active power capacity and control [15-19].

Expansion of wind power may require additional demands on regulating power. In order to keep a power system in stable operation within a specified frequency range, the active power supplied by the generation units, including energy storage devices in a system, must be adjusted continuously to match the varying load in the system. Wind farms may actively participate in grid management, including provision of regulating power and generation management. In order to deal with large scale power fluctuations, some spinning reserve may be kept in wind turbines. In this case, the wind turbine may have to operate at a lower power level than the available power level, which means a reduced utilization of the fuel free energy, a reduction in generation, and hence reduced revenues.

Power balance aspects need to consider all power exchanges related to the concerned area. However, as wind power is fluctuating due to the fluctuating nature of wind speed, the active power generation of a wind turbine is limited by the available power based on the wind speed at a certain time. Forecast of wind speed and wind power is very important to arrange the power production and active power reserve in the power system operation. Researchers are making efforts to improve the accuracy of the forecast of wind speed and wind power.

The use of the fast power control of the HVDC systems is very effective for keeping the power deviations within the desired range. Obviously, larger wind power penetration, especially, from the centralized wind farms, such as offshore wind farms, will demand higher regulating abilities of the power system. Local combined heat and power units (CHPs), though small in capacity of each unit, may play an important role if large number of such units exists in a power system, like the Danish power system. Those CHP units may contribute to the power balance of the power system and can participate in the power market. Large scale energy storage system may be technically suited for this purpose, though nowadays intensive research is needed to make the solution an economic one. Heat storage systems can also contribute, since the storage system can decouple the heat production and power production. They can thus give more freedom for CHPs (large thermal units or small local units) to perform power control and frequency regulation.

Optimization of regulating and reserve power will enable the cost effective utilization of the capacity of the available generation units. Such optimization would depend on the accuracy of the wind power and load forecast, electricity market structure and pricing shcemes. Accurate wind speed forecast would enable to maximize profits and minimize risks.

In summary, research activities on wind turbine frequency response and power balance issues are being conducted around the following topics:

- Provision of regulating and reserve power from large wind turbines/farms,
- Forecast of wind speed and wind power (see next section),
- Wind power fast transfer from HVDC and application of energy storage technologies,
- Generation and load management under electricity market.

Wind power variability and prediction – relevance in power system planning, design and operation

In order to be able to reach the targeted high wind energy penetration levels specified in national and international policies and plans, methods, models, tools and solutions for understanding and handling wind power variability are essential [20, 21]. More specifically, the Danish research efforts have the goal to improve power system and wind power plant functionality and to seek solutions for improving conditions for developing reliable and secure power systems and enabling considerable amounts of energy to be contributed from wind power. Efficient large scale integration of wind power in power systems requires development and utilization of methods combining physical models, meteorological models, modeling of wind farm behavior in the power system and statistical methods. This includes planning, design and operational phases.

Large offshore wind farms may inject significant power fluctuations into power systems. Such power fluctuations may affect power systems operation if this is not appropriately balanced. For example, the offshore wind farm Horns Rev A in Western Denmark produces more intense active power fluctuations than the aggregated wind power produced by land based wind farms in the system – see Fig. 2 which shows active power fluctuations within a day. The power gradients may reach 15MW per minute, thus the 160MW wind farm could have the output power change between zero and the rated power in 10–15 minute [16]. The system power balancing is involving connections to neighbouring countries, and could be worsened by the deviations from the planned power exchange between Norway and Sweden (two dc links). The total power fluctuations and deviations would in that case be seen in deviations of the power exchange between Western Denmark and the Northern Germany, UCTE synchronous area.

In planning, Denmark needs to be able to quantify the power fluctuations that may be experienced with the planned wind power development from today's 20 % to future 50 % of electricity consumption. In that sense, the needs for new ways of balancing the wind power fluctuations must be understood and quantified, e.g. demand response and other adjustable sources of renewable electricity generation. Wind power variability and predictability input is needed, and high quality of this input is essential for simulations to support market design, secure operation, short and long term planning [22,23].

Control and regulation of energy systems are strategic focus areas in Danish research programmes. An emphasis of a central project activity is on obtaining better wind forecasts for a more precise balancing of a power system towards 50 % wind power.

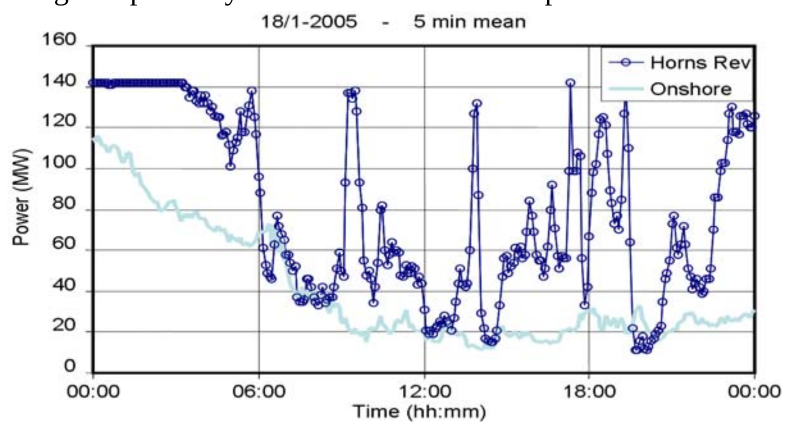

Fig. 2. Wind power variation during a day, *Source: DONG Energy and Vattenfall*.

In wind integration studies, the normal approach is to scale historical time series of wind power. However, because of the Danish strategy to build massive amounts of offshore wind power, concentrated in a few areas, the dynamics of the future wind power fluctuations are expected to change significantly, and be magnified by such concentration of wind generation capacities. A report from Danish Energy Authority 2007 identifies the future offshore wind farm sites, and this indicates a very strong concentration of wind power especially in the Danish North Sea area. Furthermore, several other countries have plans to develop offshore wind farms close to the Danish territories in the North Sea. With unstable weather, and especially in storm situations, this will call for new planning and operation tools to quantify and to forecast the future wind power fluctuations, and to develop strategies to mitigate and balance the fluctuations.

Some of relevant core projects (recent and ongoing) are listed below:

- Power fluctuations from large wind farms – models for simulation and prediction of wind power fluctuations.
- Mesoscale atmospheric variability and the variation of wind and production of offshore wind farms.
- Wind resource assessment projects using mesoscale modeling for Egypt, India, China and South Africa in cooperation with national competences and research centers [24,25].
- EU 5th and 7th Framework Programme projects regarding short term prediction of wind power
    - NORSEWIND (project # 219048)
    - SAFEWIND (project # 213740)
    - ANEMOS (project # 64848, ENK5-CT-2002-00665)
- The EU 7th Framework Programme projects TWENTIES, which is the largest R&D project in Europe regarding integration of wind power in power systems. In this project, Risø DTU will provide simulations of wind power variability and predictability with special focus on storm situations in the whole North Sea area and the impact of storms on the balancing of the North European power systems.

Internationally, there is an increased focus on research in wind power variability. IEA Wind annex 23 arranged a back-to-back workshop on Offshore Wind Farms – Wake Effects and Power Fluctuations in February 2009, with contributions to the power fluctuation session from Denmark (Risø DTU and DTU Informatics), Germany (ISET), Norway (Vindteknikk), USA (AWS) and the Nederlands (ECN). In parallel, a set of research work towards modeling and forecasting wind power variability has recently been initiated in the current European project SafeWind, by CSIRO and a number of university research centres in Australia, as well as in the USA.

Unit Commitment with High Wind Power Penetration

Integration of large scale wind power into power systems brings great benefits by reducing green house gas (GHG) emission and dependence on the conventional fossil fuels. On the other hand, it creates challenges to the planning and operation of power systems due to the variability and uncertainty of wind power. It is an obvious option to obtain more reserves to accommodate the increased variability and uncertainty of wind power from the technical perspective. But it may not be necessary and not an economic solution since the probability of high reserve request is quite low. Therefore, it is essential to incorporate the variability and uncertainty of wind power into the planning and operation process of power systems with high wind power penetration.

Unit commitment is a planning tool for system operators to ensure the reliable operation of power systems and for generation companies to maximize their profits from the power markets. The unit commitment is currently done on a day-ahead basis [26] as shown in Fig. 3.

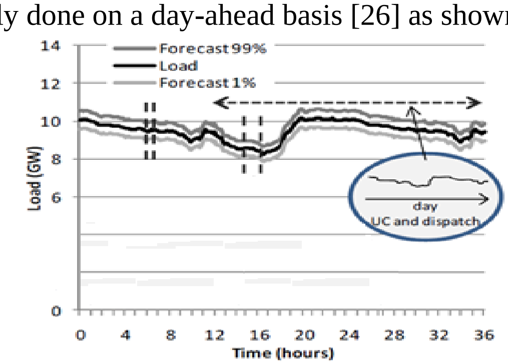

Fig. 3. Unit Commitment Process [27]

Unit commitment with high penetration of wind power is much more challenging than it used to be. The uncertainty brought by increased wind power penetration is shown in Fig. 4. Compared to Fig. 3, much bigger uncertainty and variability are shown in the net load in Fig. 4. In the existing literature, there are two categories of methods to incorporate the variability and uncertainty of wind power in the unit commitment. The first one is to include the wind power uncertainty in the day-ahead unit commitment framework. Stochastic programming methods with increased reserve have been investigated in [27], [28] and case study results show that the proposed stochastic methods with a proper amount of reserve can reduce wind power curtailment and increase the robustness of the day-ahead unit commitment schedule. A security constrained stochastic unit commitment model with wind power uncertainty modelled has been proposed in [29] for the day-ahead unit commitment of power systems with high wind power penetration. The network constraints have been considered in [30] for the day-ahead security constrained stochastic unit commitment method.

Another category of unit commitment methods for power systems with high wind power penetration has proposed to implement intra-day unit commitment on top of the day-ahead unit commitment schedule. The intra-day unit commitment makes use of the newest wind power forecast data and updates the unit commitment schedule in order to reduce the reserve requirement. With the proposed intra-day unit commitment concept, the market with a large amount of wind power can recommit based on the updated wind power forecast [31-33].

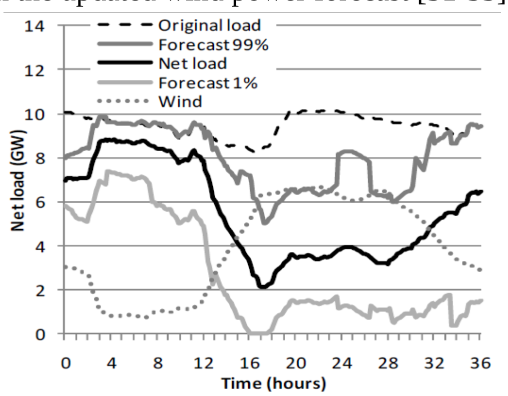

Fig. 4. Uncertainty in the Net Load with 20% Wind Power Penetration

Modeling of wind turbines and wind farms

Wind turbine technology has been subjected to a continuous transformation and development recently. As wind turbine size becomes larger, wind turbine designs are progressing from fixed-speed, and stall-controlled, to pitch controlled, and variable speed, the direct-driven wind turbine without gearboxes receive increasing attention. The wind turbine design objectives have also changed over the years from being convention-driven to being optimized-driven within the operating regime and market environment. The present general availability of low-cost power electronics increasingly supports the trend toward variable speed turbines. Today, the wind turbines on the market mix and match a variety of innovative concepts with proven technologies for both generators and power electronics [34]. The survival of these wind turbine technologies is strongly conditioned by their ability to support the grid, to handle faults on the grid and to comply with the stringent requirements of the grid codes.

All these challenges have initiated as result an important research activity directed towards integration of large wind farms within the electrical power grid. In order to facilitate investigations of wind power grid integration and enhance the development of innovative grid integration techniques, dynamic wind turbine/wind farm models have to be developed into appropriate power system simulation tools. For this purpose several power system simulation tools, such as e.g. DIgSILENT, PSS/E, SIMPOW or PSCAD/EMTDC exist. These tools include built-in models of generators, network components and allow for load flow simulations and dynamic simulation of power systems. Models for wind turbines and wind farms are not a standard feature within these power system simulation tools. It is therefore essential to develop appropriate wind turbine and wind farm models for power system analysis and to incorporate these models into power system simulation tools.

The goals of several Danish research projects have been to develop generic dynamic models and control strategies for different wind farms technologies, with the aim to optimize their operation and participation in the grid support (fault ride-through, active and reactive power control, frequency control and voltage control) [35-37]. These models have to correctly represent the dynamic behavior of the wind turbines in order to predict critical operation conditions at the one hand and to improve their dynamic performance at the other hand. The detail level of the developed models is related to the time frame of the simulation. For analysis of power system stability and the wind turbine's response to grid faults or fluctuating wind loads a respective time frame from milliseconds to minutes is relevant.

Application of dynamic wind farm models as part of power system simulation tools allows for detailed power system studies and enhances the development of appropriate control techniques for wind power grid integration. Nowadays, at Risø DTU in Denmark, models and control strategies for three different types of wind turbines are developed and implemented in the dedicated power system simulation tool DIgSILENT Power Factory, which is assessed to be an appropriate power system software, including

- Fixed speed active stall wind turbine concept
- Variable speed doubly-fed induction generator wind turbine concept
- Variable speed multi-pole permanent magnet synchronous generator wind turbine concept

These models and control strategies facilitate the assessment of the dynamic performance of wind farms both in normal or fault operation [35-37].

These wind turbine concept models can be used and even extended for the study of different aspects, e.g. the assessment of power quality, control strategies, connection of the wind turbine at different types of grid and storage systems. In a broader sense modeling can be used to design and optimize the future power system, when even larger amounts of wind power must be integrated, so that investment risks can be minimized. The continuous development of such analysis tools facilitates that the improved technologies for wind power grid integration can be investigated to ensure the worldwide growth of wind power use.

Some of relevant core projects (recent and ongoing) are listed below:

- Operation and control of large wind turbines and wind farms
- Simulation platform to model, optimize and design wind turbines
- UpWind – Integrated Wind Turbine Design (project funded by the European Commission)
- TWENTIES – Storm control (project funded by the European Commission)
- Grid fault and design-basis for wind turbines
- Integrated design of wind power systems
- Enhanced Ancillary Services from Wind Power Plants

DC grids for integration of large scale wind power

Recently, based on the initiative from the Danish standardization committee, IEC has initiated a working group to prepare a new standard IEC 61400-27 [38] on electrical simulation models for wind power generation. The working group, convened by Risø DTU, consists of more than 40 members from 14 countries including TSO's, wind turbine manufactures, suppliers and research communities. This activity has started in 2010 and has as goal to define standard generic dynamic models for wind turbines and wind farms. These generic models are developed to represent wind power generation in power system and grid stability studies. Moreover the attention is also drawn to the specifications of validation procedures for the generic models of wind turbines and wind farms.

Smart grids and demand side management

In order to compensate some of the fluctuations introduced in the network by the large wind power penetration, one of the smart grid features, the electrical vehicles (EV), can be used. In power systems with a high wind power penetration, many hours with surplus of electrical power production might be expected. This energy could be consumed locally through demand side management of local consumers, especially the electrical vehicles, since the EV batteries could also discharge to the grid on request when the grid is in lack of power. This means that the EV can act both as a controllable load and a distributed generator. The batteries could be aggregated as large energy storages, and be used for balancing purposes both in isolated and integrated systems [39]. Fig. 5 shows a simulation result where EV is used as an energy-storage in connection with the Load Frequency Controller for the Western Danish power system [40]. Here two different capacities for the aggregated battery is used: one is that the battery size is equal to the size of the normal expected spinning reserve (case V2G) and another that the battery size is 5 times higher (case V2G+). In Fig. 6, the battery state of charge in the two situations is shown. From the figures it is can be seen, that the aggregated battery really releases the load frequency controller demand on the generators in the network, and it also reduces the power exchange deviations with the neighboring countries (not seen in these figures). However, it is also seen, that in the first case, with the small V2G system, the systems reaches the lower limit for state of charge rather soon, whereas the larger system has sufficient power to compensate the system for a full day. However, if the situation in the network still remains and there is a need for compensating power also the next day, then the system will go to its limit. However, in such long time cases, it should be possible to change the set-points for the power plants or for the power exchange with neighboring countries appropriately, and then keep the system in stable operation.

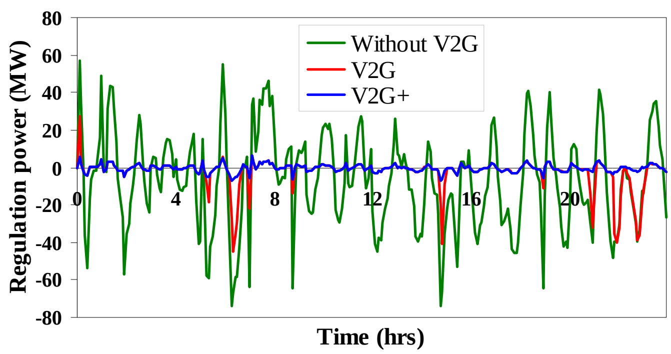

Fig. 5. LFC order of generators for the reference case without V2G, V2G base case and V2G+ case.

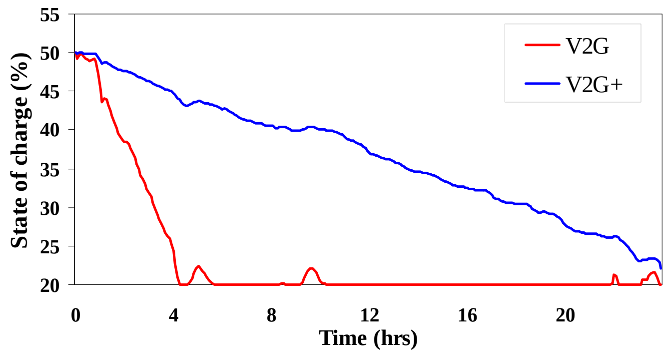

Fig. 6. Battery state of charge from V2G base and V2G + simulation cases [40]

In [39] it is also shown how V2G can be used for frequency stabilization in smaller islanded distribution network grids with high wind power penetration. Simulations have been made for instance for step load changes and loss of generation in the network, and the results show that the V2G ensures a faster and more stable frequency regulation than the conventional generators. This is due to its smaller time constant, and the storage uses here a droop frequency control to adjust the active power level of the aggregated battery storage.

Initial research activities of wind energy at the Sino-Danish Centre for Education and Research (SDC)

SDC wind energy sub-theme plans to connect with the research activities of Danish research consortium for wind energy and *European Energy Research Alliance* (*EERA*) to work mainly in some core research areas of wind power technology. Among other research topics, grid integration of wind power would be the initial focus. The wind energy sub-theme of SDC has initialized a number of PhD projects in 2011, including

- Advanced coordinative control of wind power conversion system.
- Wind farm integration into the power system.
- Coordinated Control of Wind Power Plants and Energy Storage Systems.
- Development of micro-actuar systems for wind turbine rotors.
- Dynamic modelling and ancillary services in power systems with large scale wind power.

Conclusion

This paper presents an overview of the recent research activities and tendencies regarding grid integration of wind power in Denmark and some related European activities by the team of experts of the wind energy sub-theme of the Sino-Danish Centre for Education and Research (SDC). The grid integration of wind power is focused. The PhD projects of the SDC wind energy sub-theme are presented as well.

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