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CIGRE US National Committee
2017 Grid of the Future Symposium

Role for Adjustable Speed Pumped Storage in the Grid of The Future

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SUMMARY

This paper discusses the subject of Grid-Scale Adjustable (aka Variable) Speed Pumped Storage technology in Europe and Japan and suggests a possible role as part of a Balancing Authority in the US Grid of the Future. Questions are posed about the consequences of changing system inertia and how inertial energy stored in a DFIM rotor can be controlled and used to maintain frequency and power balance.

With increased wind and solar capacity, distributed storage, and retirement of large inertia steam turbine driven base-load generators, there is a need for system impact studies that will demonstrate how adjustable-speed pumped storage units, with fast kinetic inertial response, can meet existing and future grid interconnection requirements.

KEYWORDS

Pumped storage, Doubly Fed Induction Machine (DFIM), Adjustable Speed, Inertial Response, Fast Power Control.

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INTRODUCTION

In the early 1990's, two Japanese utilities, Kansai Electric and Tokyo Electric, installed adjustable speed pumped storage units. The motivation for this was their need to reduce the amount of imported fuel used by combustion turbine driven generators for frequency regulation during periods when pumped storage units were operating in the pump mode. It was realized that if pumped storage units could regulate frequency in pump mode, then combustion turbine generators would no longer be required to provide frequency regulation service. It was also recognized that other plant and system benefits would be realized with adjustable speed pumped storage units.

The first commercial installations were at the Yagisawa and Ohkawachi pumped storage plants. The installation at the Yagisawa plant was an 85 MW unit that was converted from single speed 150 rpm synchronous motor/generator to a doubly fed induction motor/generator with speed that is adjustable over the range 130 to 156 rpm. The Ohkawachi plant is a four unit pumped storage plant with two adjustable speed motor/generator units with a speed range of 330 to 390 rpm.

Since the initial units were installed in Japan, there now are more than thirty adjustable speed pumped storage units in operation world-wide. The majority are in Japan and others are installed in Europe. To date there are no grid-scale adjustable speed pumped storage units in the United States although several new pumped storage projects are in the feasibility and licensing phases and some may include adjustable speed units.

In 1994, EPRI, with support from the National Hydropower Association, approved a study of the Japanese adjustable speed pumped storage development. The study report is titled "Application of Adjustable Speed Machines in Conventional and Pumped Storage Hydro Projects" [1] and was published in 1995.

In 2014, DOE funded a study of advanced pumped storage hydro. The effort was led by Argonne National Labs (ANL) with an engineering team comprised of: MWH (now part of Stantec), Siemens PTI, Energy Exemplar and National Renewable Energy Laboratory (NREL). The study results are available in a report titled "Modeling and Analysis of Value of Advanced Pumped Storage Hydropower in the United States". [2] The ANL study was part of a larger DOE Hydro Vision effort under their Wind and Water program.

An IEEE-PES Task Force named "Advanced Pumped Storage Modeling" was started in 2014 by the IEEE Power Energy Society (PES), System Dynamic Performance Committee. There are also several CIGRE study groups that are investigating various aspects of advanced pumped storage technologies with adjustable speed pumped capability. The IEEE Task Force scope includes three advanced pumped storage modeling technologies: Doubly Fed Induction Machines (DFIM), Converter Fed Synchronous Machines (CFSM) and ternary units. A common characteristic of these hydro storage technologies is that they can change power in both pump and generation modes and therefore can provide ancillary services in both modes.

The most prevalent of the three technologies is the grid scale reversible doubly fed induction motor/generator (DFIM) with a three-phase solid rotor and a sinusoidal field whose frequency can be adjusted to change rotor speed in a range above and below a nominal synchronous speed. There are approximately 33 adjustable speed doubly-fed induction pumped storage units in operation around the world today.

An estimate of total installed capacity of operating pumped storage units in the world is in the range of 130 to 150 GW and there are several more in the planning, design and construction stages. To date there are only a few CFSM and Ternary units in operation and they have capacity ratings up to 150MW. Therefore, the grid scale DFIM units, with their greater number and larger capacity, are the focus of this paper.

CHANGING GRID SYSTEM INERTIA

There is a noticeable change in system inertia as more and more variable wind and solar sources, with minimal to no inertia, are coming on-line and large capacity coal, oil and natural gas powered generators are being decommissioned. The impact on system inertia is being observed in large interconnected systems around the world. The changing system inertia has been documented for the grid in Europe [3], [4] as well as in the United Kingdom.

Changing system inertia has obvious consequences from a system operating perspective and is most noticeable with regard to system frequency control, ramping and post system-event response [5]. System operators in Europe and UK are addressing this change by creating ancillary service markets and payment schedules that recognize the ability of advanced storage technologies to provide extra fast grid level power response services including fast inertial response. There are several new pumped storage plants in Japan and Europe that have units with advanced pumped storage technology. The decision to install units with advanced technologies is driven by the need for more efficient operation as well as the ability to provide fast response to system events.

One example is in the UK, where National Grid has created a new class of frequency regulation called “Enhanced Frequency Response (EFR)” [6]. The EFR regulation is for units that can provide an initial response within one second or less of a system event followed by nine seconds of sustained response.

Australia. A recent example of the impact of low inertia renewables on system operation was experienced in Australia on September 28, 2016. The report on the blackout event includes the following in its list of conclusions: “The generation mix now includes increased amounts of non-synchronous and inverter-connected plant. This generation has different characteristics to conventional plant, and uses active control systems, or complex software, to ride through disturbances. With less synchronous generation online, the system is experiencing more periods with low inertia and low available fault levels, so Australian Energy Market Operator (AEMO) is working with industry on ways to use the capability of these new types of power generation to build resilience to extreme events.” [7]

Japan. Japan has been in the lead as a developer of advanced pumped storage technologies followed recently by European manufacturers. There are 35 pumped storage plants in Japan and of these eight have adjustable speed units with other projects in planning and construction. There are 14 operating adjustable speed units with capacity in the range from 85 MW to 475 MW. The Japanese experience with dynamic response of its adjustable speed pumped storage units has been shown to be effective during major system events such as earthquakes and most recently the March 2011 Fukushima nuclear plant outages.

A recent installation at the Kyogoku pumped storage plant on Hokkaido has 200 MW adjustable speed motor/generators with a speed range of 475 to 525 rpm. Because Hokkaido is an island system with significant solar and wind power installations the system frequency experiences significant unpredictable fluctuations due to rapidly changing wind and cloud conditions. To address the frequency regulation needs of the Kyogoku pump storage units have a unique charge/discharge flywheel control system.

ADVANCED PUMPED STORAGE IN THE US

There are 42 grid scale pumped storage plants in the US with a total installed capacity on the order of 22 GW [8]. The plants range in size from the six-unit 3,003MW Bath County plant in Virginia to the two unit 40 MW Lake Hodges project in California. The Lake Hodges plant went into commercial operation in 2012 and is the most recent US project to enter commercial service. To date, there are no grid-scale DFIM adjustable-speed pumped storage units operating in the US.

An obvious question is: If new pumped storage plants, with advanced pumped storage units are being installed in Japan and Europe, then why aren't any being installed in the United States? Part of the answer is that US pumped storage plants are not able to receive revenue (compensation) for all the capabilities and services.

Prior to the issuance of FERC rule 888 in 1986, pumped storage plants were constructed with reversible single-speed synchronous motor/generators and operated on the principle of energy arbitrage; that is, pump with low cost energy from base load units in the late night to early morning hours and generate at mid-day peak demand periods.

Several power market refinements have been adopted since FERC 888 was adopted; for example: FERC Order 719, A & B "Wholesale Competition in Regions with Organized Electric Markets" 2008, FERC 764 "Integration of Variable Energy Resources" in 2012, FERC 2003 interconnection procedures, and FERC 1000 "Transmission Planning and Cost Allocation by Transmission Owning and Operating Public Utilities". A consequence of these Orders and refinements is that the traditional arbitrage business model for pumped storage plants no longer fits power market structures. Industry organizations along with project developers brought this situation to the attention of FERC. In November 2016 FERC acknowledged the situation and issued a Notice of Proposed Rulemaking (RM-16-23-000) "Electric Storage Participation in Markets Operated by Regional Transmission Organizations and Independent System Operators". The NOPR addresses the fact that existing pumped storage plants and proposed new pumped storage developments "are (1) [not] properly valued in current energy market constructs; and (2) [not] compensated adequately or uniformly for the grid benefits, including services, they can and do provide in the various markets across the country."

Existing resources, such as pumped storage, are often relied upon for capabilities that do not have defined market revenue streams [1] such as fast inertia and fast voltage control response capabilities. As a result, establishment of new participation models for electric energy storage, as contemplated in the NOPR, will be critical to encourage development of new energy storage projects. Energy storage technologies, large and small, are complimentary rather than in competition with each other. As such, any energy storage technology should be

[1] This is especially the case for new pumped storage hydropower as market-driven procurement has favored less capital-intensive projects with shorter development lead times.

recognized and compensated for the services/benefits it provides [9], which are summarized in the list of issues associated with the subject:

1. Energy and Capacity Services:

    Energy Time-Shift (Arbitrage). An example of this type of service is the ability to deliver renewable energy on peak to better respond to customer needs.

a. Energy Supply Capacity Value storage for each block of capacity it serves, which will vary according to what part of peak demand it addresses.

2. Grid Ancillary Services:

b. Regulation and frequency response

c. Load-following and flexibility reserve

d. Energy imbalance service

e. Spinning reserve

f. Non-spinning/Supplemental reserve

g. Reactive power and voltage support

h. Black start service

3. Transmission Infrastructure Services:

i. Transmission upgrade deferral

j. Transmission congestion relief

k. Overall grid portfolio optimization and management for transmission and generation resources

While the list does not specifically mention the role that advanced storage technologies play in system dynamic performance associated with system events, FERC does. In early 2017 FERC issued a policy statement that addresses the issue of compensation for ancillary services including fast response capability, such as: frequency response, frequency regulation, and energy imbalance, load following and reactive power support; all of which can be provided by advanced pumped storage units.

As of August 2017, 19 new pumped storage project sites had active FERC preliminary permits and developers are moving forward with planning studies and preliminary designs. The project sites are in twelve states; eight in Pennsylvania and the rest of the states each have one or two projects. The largest project is 811MW and the smallest is 554MW. These projects have an estimated combined capacity of 6,073MW.

It is expected that several projects will receive FERC licenses and will move into the construction phase. This raises the question: will any of these projects have adjustable speed units? The answer is linked to the future needs of the bulk power grid, with its changing inertia due to increasing amounts of non-dispatchable renewables including wind and solar, and the need for grid-scale fast response units.

SYNCHRONOUS INERTIAL RESPONSE

In 2014 NERC created an Essential Reliability Services Task Force (ERSTF) to consider grid-system issues that may result from the changing generation resource mix. See the Summary of Analysis Table 2 in the 2015 NERC report titled "Essential Reliability Services Task Force Measures Framework Report". Table 2 has a column with the heading "Inertia trending down?" and presents the replies from nine Balancing Authority/Independent System operators. Two reply "Yes", two reply "somewhat", four reply "No too little" and one replies "No". The report also includes a discussion of the impact of renewables under the heading "Synchronous Inertial Response Measures". The subject is addressed in greater detail and suggests that there is a need for Inertia-Based Controls in NERC's December 2016 "Long-term Reliability Assessment Report" [10],

INERTIA-BASED CONTROLS

Adjustable speed doubly fed induction motor/generators in pumped storage plants have controls that can provide fast frequency response. The response is based on converting inertial energy stored in the motor/generator rotor and pump/turbine mass into power. See Figure–1 for an example of a typical frequency drop in a 1 to 10 second time frame and consider how an adjustable speed PSH unit with "fast frequency response" capability would respond.

The initial function of "fast frequency response" control is to provide arresting power in the first seconds following the occurrence of a system event. Once the frequency decline has reached its nadir a sustained response follows in the rebound period.

Adjustable speed unit response rates on the order of tenths of a millisecond have been reported. The following information is from an IEEE-PES paper [11]. "For an ASH [adjustable speed hydro] generator, both active and reactive power production can be changed very rapidly, about the order from 10 to 30 milliseconds. This is possible due to the ability to change the rotor current frequency very fast."

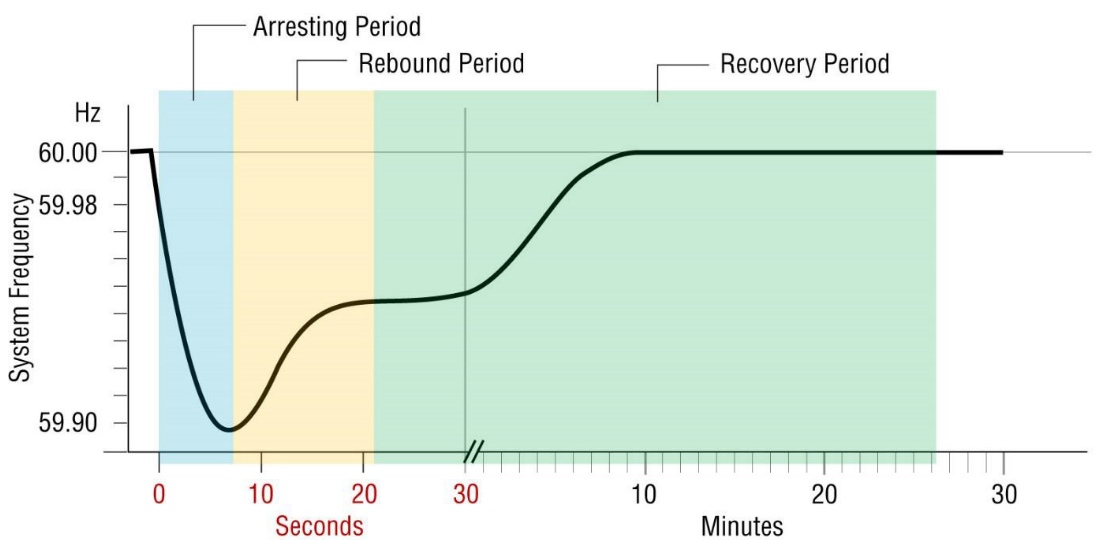


Figure – 1. Frequency Response following System Event

In the preceding explanation, the time of 10 to 30 milliseconds is the time in which a cycloconverter can change rotor current excitation frequency. In a presentation by Alstom for the Goldisthal project, the total time of a step response for change in power from zero to rated capacity by way of the cycloconverter and associated controls is given as 150 milli seconds. The 150milli seconds includes the 10 to 30 millisecond cycloconverter response time. When the DFIM response rate is compared to the rate of change of output [12] from solar and wind sources then adjustable speed pumped storage becomes an attractive source of regulation.

DFIM TECHNOLOGY

DFIM and single – speed pumped storage hydro units are both designed to convert input hydraulic/mechanical power (torque) into output electric power (current at a specific voltage) and visa versa. In many ways, a pumped storage unit with a DFIM motor/generator is similar to a pumped storage unit with a single-speed synchronous salient pole motor/generator. In both cases the mechanical/hydraulic, pump/turbine, wicket gates and turbine governor controls are basically the same. However, there are four major equipment differences between a DFIM and a single-speed synchronous machine; they are: (1) the rotor construction, (2) rotor excitation system, (3) speed/power control system and (4) three-phase rotor brush assembly. Figure-2 shows the topology for the major components of a DIFM adjustable speed motor/generator.

The stator of a DFIM is similar in construction to that of a conventional synchronous machine; it has a multi-pole configuration with the number of poles determined by the nominal synchronous speed. Selection of the synchronous speed is linked to pump/turbine and hydraulic design characteristics [13]. A doubly fed induction motor/generator uses a solid smooth air gap rotor with laminated construction instead of a salient pole rotor as used in single-speed synchronous machines. A three-phase sinusoidal magnetic field is established on the rotor with alternating current provided by a voltage source frequency converter. The frequency and magnitude of the sinusoidal current that creates the rotor field is controlled by unit controls. The result is that rotor speed can be controlled by changing the frequency of the rotor field current. Fig - 4 illustrates the relationship between rotor mechanical speed and rotor field frequency.

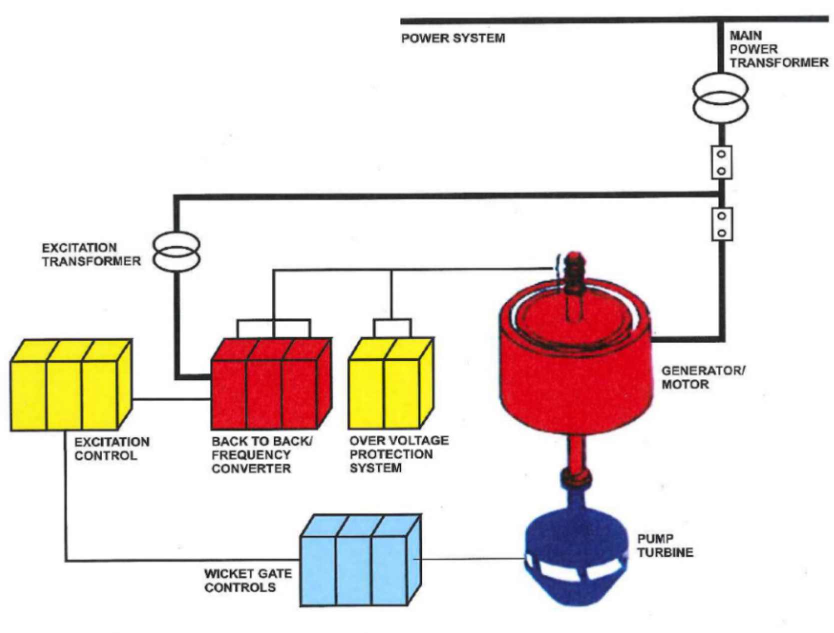
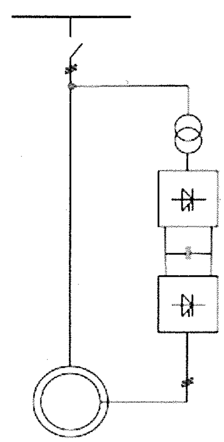


Fig - 2 DFIM Major Equipment Configuration



The preferred configuration of a doubly fed induction motor/generator uses a voltage source frequency converter connected to the rotor; see Figure-3. The frequency converter provides sinusoidal current needed to create a three-phase magnetic field on the rotor. The capacity rating of the frequency converter is roughly proportional to the slip.

Figure - 3 frequency converter connected to the DFIM rotor

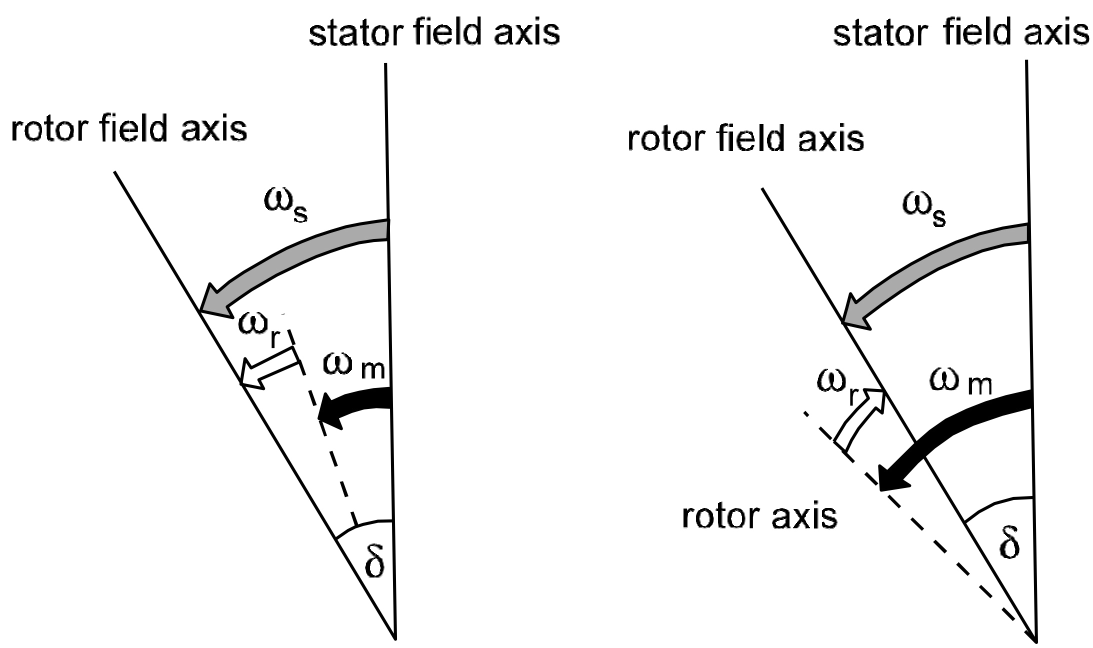


Fig - 4 Speed relationships

Electrical Mechanical Speed Relationships. Range of rotor speed from: $W_m < W_s$ to $W_m > W_s$

$$W_s = 2\Pi f_s, \quad W_r = 2\Pi f_r, \quad W_m = \frac{P}{2} 2 \frac{\Pi}{60} \text{ r.p.m.}$$

W_S stator rpm $\quad$ f_s system frequency
W_R rotor rpm $\quad$ f_r rotor field frequency
W_m mechanical rpm

KINETIC ENERGY – FLYWHEEL EFFECT

Kinetic energy stored in the rotor inertia of a doubly fed induction motor/generator can also be controlled by changing the rotor field excitation frequency. While stator frequency remains constant, the kinetic energy is stored or retrieved from rotor inertia by increasing or decreasing rotor speed. The change of kinetic energy associated with the change of rotor speed can be used for rapid stabilization of power fluctuations caused by faults or other disturbances in the power system [14].

The potential use of kinetic energy and fast frequency response is also described as the "flywheel effect" in the discussion and comments to FERC [15] rule 764 (Integration of Variable Energy Resources). The discussion makes the point that a MW of reserve capacity from a fast-ramping resource provides more regulation value to the grid per MW than a slow-ramping resource. Some storage resources that provide generator regulation service, such as high speed flywheels, can dampen variations much more quickly than can traditional generators.

For a reference documenting the system damping capability of an Adjustable Speed Machine see [16]. This paper describes the damping capability of an adjustable speed unit at the Ohkawachi Pumped Storage Plant on the Kansai Electric System in Japan. In the discussion, the authors note that unit number four was in operation when the Hanshin earthquake occurred on the morning of January 17, 1995, and they report that the machine absorbed power disturbances in random spikes [17].

DFIM ADJUSTABLE SPEED HYDRO, POWER/SPEED CONTROL OPTIONS

Single-speed synchronous machines with turbine governor controls are used in conventional pumped storage plants. The input to the turbine governor control is mechanical speed and wicket gate position and is used to control mechanical power (torque) via water flow. Since the speed of a single-speed synchronous motor/generator is locked (synchronized) to system frequency, then the speed adjustments are determined by wicket gate servo motor operating times and water column acceleration time.

In a pumped storage plant with a DFIM, there are two controllable variables; gate position and rotor field speed. The rotor field exciter time constant, including motor/generator time constant, is shorter than the time constant of the turbine governor including water column time constant. Therefor it is possible to change the rotor field speed faster via electronic controls than it is to change mechanical speed of the pump/turbine water wheel by wicket gates. In the steady state, unit controls select the optimum relationship between gate position and rotor speed to give the desired power and efficiency. However, when a system event occurs, rotor speed control can be used to provide fast frequency/power response.

Three control approaches have been developed for use with DFIM adjustable speed pumped storage units:

1. Fast Power Control: Electric power is controlled by the rotor excitation converter, and the rotating speed is controlled by the turbine-governor adjusting the gate position.
2. Fast Speed Control: Rotor speed is controlled by the rotor excitation converter, and the electrical power is controlled, in generation mode, by turbine-governor gate position adjustment.
3. Fast Speed (Slip frequency) Control with governor free operation.

The Fast Power Control option is the prevailing control method and is being used with a majority of existing DFIM adjustable speed units. The Fast Speed Control approach has been evaluated and the response to transient events is found to be different from that of the Fast Power Control response and in some cases may not meet system dynamic performance requirements.

The third control option uses a combination of Fast Power and Fast Speed Control. With this control the output power is normally controlled by adjusting wicket gates and the rotor frequency converter control to adjust the speed and maintain optimal speed similar to that of the Fast Speed Control. In the event of a large disturbance, with steep RoCoF, an additional compensation signal is applied to both rotor frequency converter control and wicket gate control.

TRANSMISSION INTERCONNECTION STUDIES

The next task after a control option is selected is to carry out transmission interconnection studies including system impact studies. The interconnection application process is carried out according to FERC regulations as set out in its rule 2003. FERC is revising its LGIA (large generation interconnection application) rule number 2003. The FERC document that describes the proposed changes to the interconnection application process includes a section titled "Material Modifications and Incorporation of Advanced Technologies". The revised rule will require that Transmission Providers develop:

- A definition of permissible technological advancements pursuant to an interconnection request that the interconnection process can accommodate; and
- An accompanying procedure that will be used to accommodate the incorporation of technological advancements to interconnection requests for synchronous and non-synchronous generating facilities.

In addition, the Commission proposes that these definitions should contemplate advancements that provide cost efficiency and/or electrical performance benefits.

These requirements raise the question: will transmission owners include adjustable speed pumped storage in their list of advanced technologies, and, if so, then what excitation model and control option will be used to make System Impact Studies?

ADJUSTABLE SPEED PUMPED STORAGE IN A BALANCING AUTHORITY

Consider a balancing authority that has a DFIM adjustable speed pumped storage unit together with several conventional single-speed synchronous generators. Since the DFIM adjustable speed machine can respond faster than the conventional units, will there be concern about the interaction among the units as they attempt to converge to a new stable operating state after a system event? System impact studies would determine if single-speed synchronous units can exchange synchronizing power with the faster DFIM adjustable speed PSH unit's response [18] and reach a new stable steady state. For a discussion of how a balancing authority could function with a DFIM adjustable speed pumped storage unit see CIGRE Technical Brochure 316,

> "Defense Plan Against Extreme Contingencies" Task Force C2.02.24, April 2007. Section 2 "Overview of Existing Defense Plans" and part 2.11 "Proposal for a new response-based Wide-Area stability and voltage Control System (WACS) for the Western North American interconnected power system"; Pages 58-70.

CONCLUSIONS:

- Transient dynamic response of DFIM adjustable speed pumped storage units in the planning and design phases needs to be evaluated on a case by case basis according to control options and system dynamic performance requirements.

- Given the fast response of a DFIM adjustable speed pumped storage unit, then it remains to be determined if system impact studies can be made with Laplace transform based software or if an EMTP differential equation approach is required?
- There is a need for a set of generic models with data for the three control options that can be used for transmission interconnection system impact study applications.
- The question remains to be answered: "Will grid-scale storage, with DFIM adjustable speed motor/generators, be part of the Grid of the Future"?

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