Interconnection of HYDROMATRIX ® units with electric power systems

HYDROMATRIX®, what is it?

Basic idea of HYDROMATRIX®:

- Using of existing dams and weirs (for irrigation and navigation) for production of renewable energy
- Installation of a certain number of identical units in a “matrix” arrangement (with rows and columns)
- Simple design with lows costs and minimized effort in civil works

Different types of generator

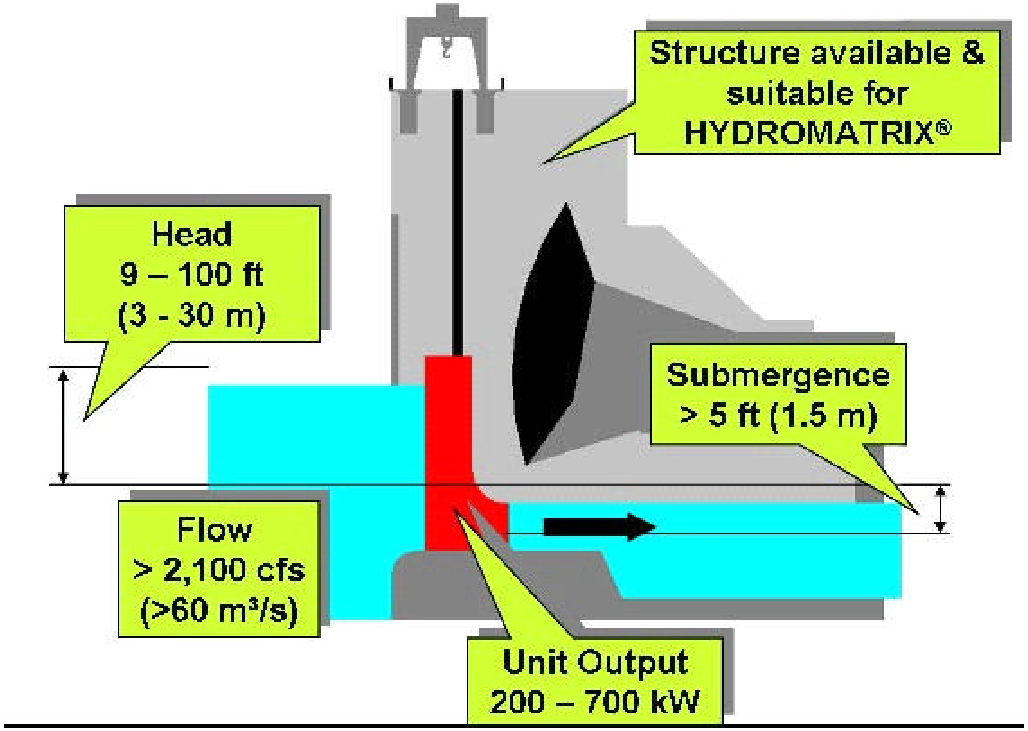
- Induction type generator with reactive power compensation
- Permanent excited synchronous generator

Reference project:

Jebal Aulia / Sudan

80 units each 380 kW
asynchronous type with reactive power compensation

The HYDROMATRIX® concept



Hydraulic application range:

- Discharge more than approximately 60 m³/s
- Head from 3 m to 30 m
- Draft tube exit submergence of about 1.5 m
- Structure available and suitable for HYDROMATRIX® modules

Components of a HYDROMATRIX® system

§ Module

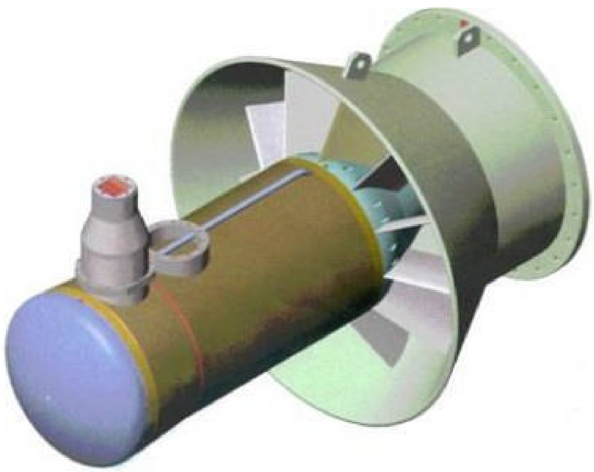
The HYDROMATRIX® system basically consists of a compact arrangement of turbine-generator units (TG-units) including trash racks, draft tubes, space for hydraulic power unit, electric switchgear and control systems

§ Turbine-Generator unit (TG-unit)

With the ongoing developments and the specific needs for each application VA TECH HYDRO has developed different types of TG-units

Asynchronous type

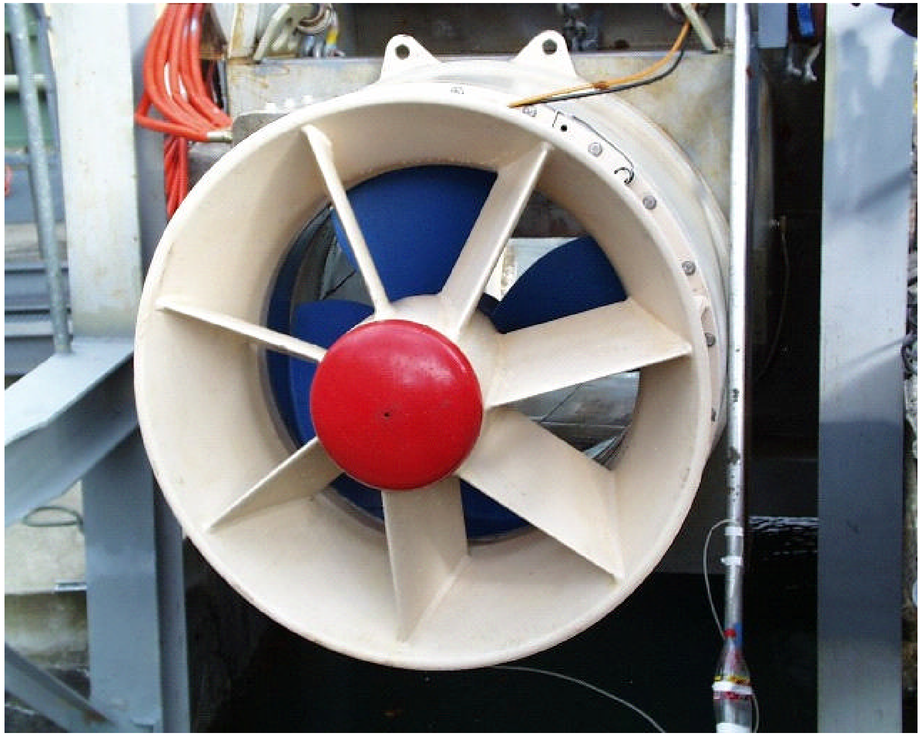
- with 2 or 3 bearings
- reactive power compensation necessary
- proven technology over decades



Components of a HYDROMATRIX® system – cont.

Synchronous type - StrafloMatrix™

- Rotor equipped with permanent magnets
- innovative integrated turbine runner-generator rotor design
- reduced weight and size
- low maintenance and service requests



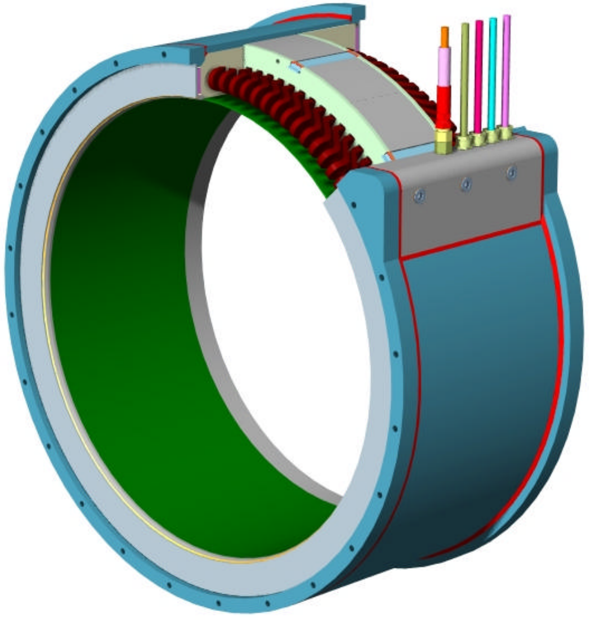
Special system features:

- load depended reactive power production
- induced voltage proportional to speed
- simple electrical equipment

StrafloMatrix™ - design features

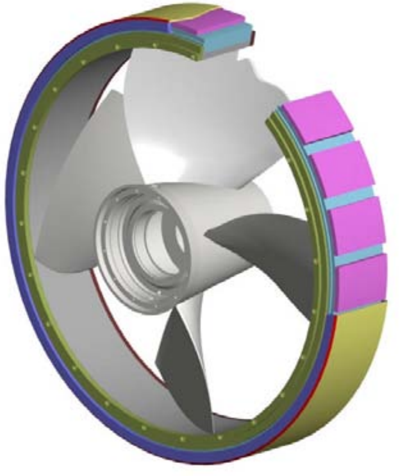
Stator

- Stator filled with electrical insulating and thermal conduction silicon based material
- Totally enclosed stator housing
- No service and maintenance necessary



Rotor

- Rotor ring direct welded to the turbine blades
- Permanent magnets glued to the rotor yoke
- Magnets protected with stainless steel cover
- Enclosed oil lubricated roller bearings



StrafloMatrix™ - design features – cont.

- Permanent magnets

  Material Properties of Permanent Magnets

  Rare earth magnets made out of Samarium-Cobalt and Neodymium-iron-boron have a very high specific energy and are therefore very well suited to be used in motors and generators

  - **Corrosion Properties**: Common NdFeB is highly susceptible to oxidation at the grain boundaries and will corrode easily. Additives or special manufacturing techniques such as rapid quenching can significantly enhance the corrosion properties
  - **Magnetic Properties**: When designing the operating point of the magnet, the negative temperature coefficient of the base materials has to be considered. The permeability of the magnets is comparable to that of air (typically μ_r=1.05)
  - **Thermal Properties**: The demagnetization curves show that the magnetic characteristics are dependent on temperature of the permanent magnets. Exceeding a defined maximum temperature can lead to either a reversible magnetic loss or to irreversible magnetic losses

StrafloMatrix™ - design features – cont.

Demagnetization Curves of Permanent Magnets

The magnetic properties of permanent magnets are shown in demagnetization curves with the temperature being the main parameter

Shapes of magnets

As most magnets are manufactured by sintering milled powder, shapes and sizes can be chosen freely within a wide range. Size restrictions are caused by the magnetization devices and by the manufacturing process

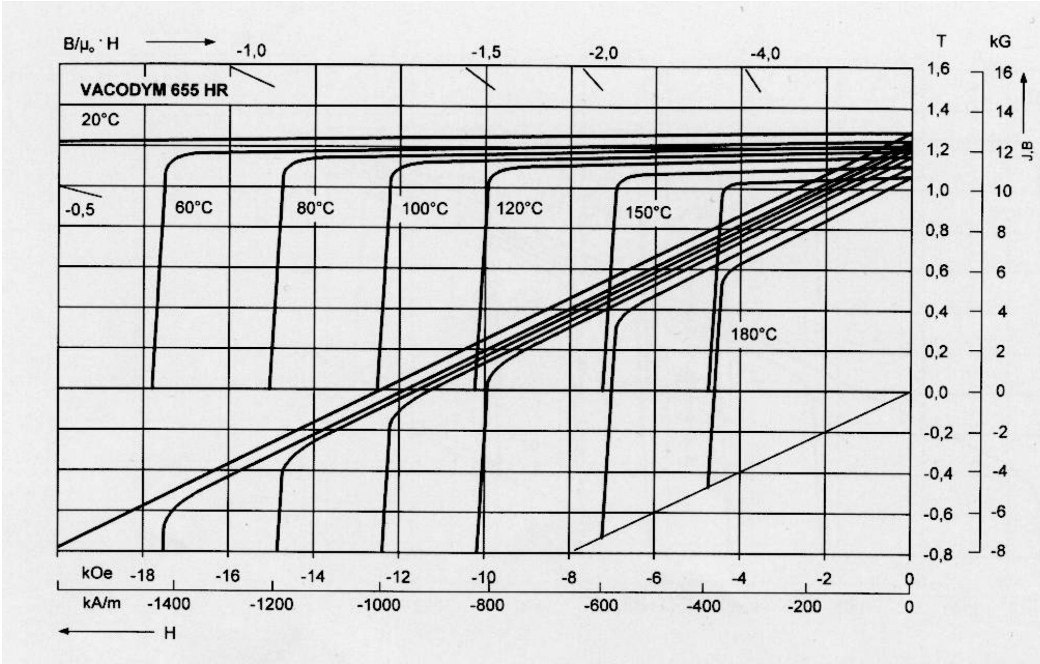


Diagram: Demagnetization Curve of a Neodymium-iron-boron magnet material (Source: Vacuumschmelze GmbH)

Interconnection of HM® units with the power system

Different regulations are established worldwide to deal with interconnection requirements which energy resources have to fulfill to be connected to power systems. In some parts of world vertically integrated electricity companies managing the entire electricity supply chain: generation, transmission and distribution

In Europe, the structure of power systems has changed immensely, as a consequence of the liberalization of the electricity market, driven by EU-legislation. The European Directive defines the framework of a liberalized market. The Directive charges the Member States to appoint one or more independent transmission system operators (TSO), distribution system operators (DSO) and regulatory authorities.

The final report by the CIRED Working Group on Dispersed Generation (1999) showed that variety in points put forward by questioner respondents. As a conclusion, the Working Group selected the following that generator must comply with to be considered as “distributed generator”

- Not centrally planned
- Today not centrally dispatched
- Usually connected to the distribution network
- Smaller than 50-100MW

Interconnection of HM® units with the power system – cont.

These criteria were also already mentioned in the definitions of CIGRE working group WG C6.01 for Development of Dispersed Power Generation (DG).

Refer to some executed projects in Austria and ongoing projects in USA and Italy, HYDROMATRIX® is designed to be connected to the distribution system considering size of individual units and the total generating output. This means that rules established for generating units of DG should apply.

If we consider the most important difference between DG and classical generation that "not centrally planned or dispatched - means that the major influences such as unit commitment or reactive power generation are out of control of the system operator" HYDROMATRIX® units behave on the way which could not be strictly classified to any of generation groups.

HYDROMATRIX® units' contribution to active and reactive power generation is <u>not controllable</u> by the system operator <u>but it is predictable</u>. Taking into account that hydrology conditions are not changing unpredictably and are not fast changes as it could be a case with wind energy generation.

European grid operators rules "Generators must be able to regulate their reactive power at every value between the upper and lower limits" are established differently in European countries. This means that for HYDROMATRIX® units application additional measure should be considered such as regulating power transformers or reactive power compensation.

Example for Implementation: Lower St. Anthony Falls/USA

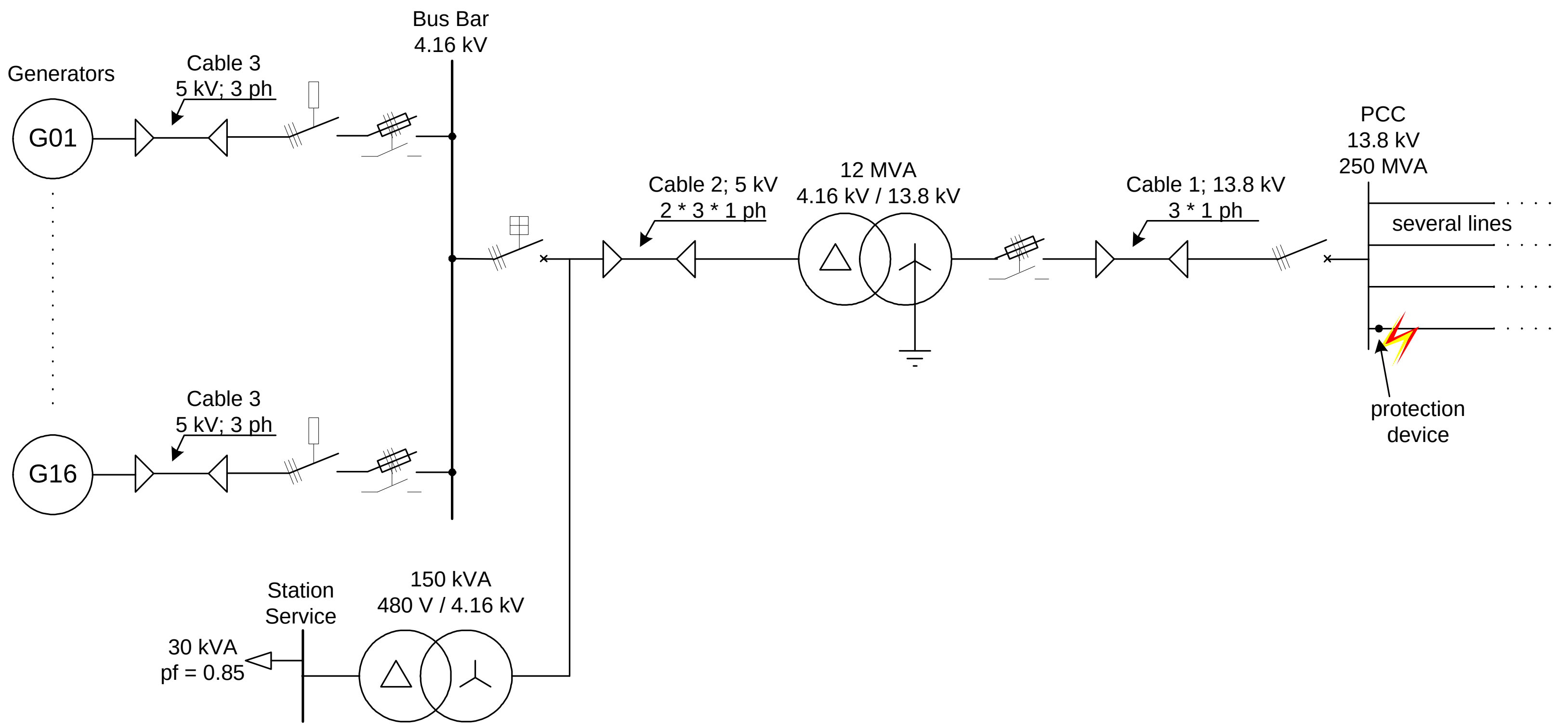
- Lower St. Anthony Falls in Minneapolis StrafloMatrix™ units has been provided which include 16 unregulated turbines and generators
- Since that total generation output of the Lower St. Anthony Falls is in the range of distributed generation guided by IEEE 1547 and that an interconnection to the grid will be done to Minneapolis distribution system, we studied the implementation of PM generators through all aspects of the IEEE 1547 regulation.
- Generator data for one units:

Rated values:

Output	700 kVA	
Voltage	4,160 V	
Current	97.15 A	
Frequency	60 Hz	
No. of Poles	22	
Speed	327.27 rpm	
Moment of Inertia	210 kgm2 (incl. turbine runner)	
Mech. time constant	0.37 sec	
Inertia constant	0.185 sec	
Characteristic reactance's:	direct	quadrature
Synchronous reactance	0.45pu	0.48pu
Transient reactance	n.a.	n.a.
Subtransient reactance	0.28pu	0.28pu

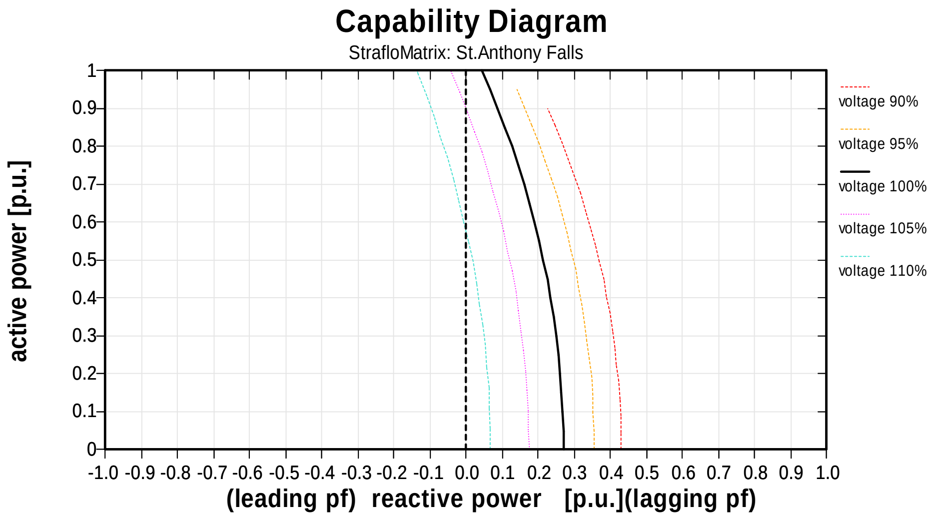
Analysis of IEEE 1547 requirements

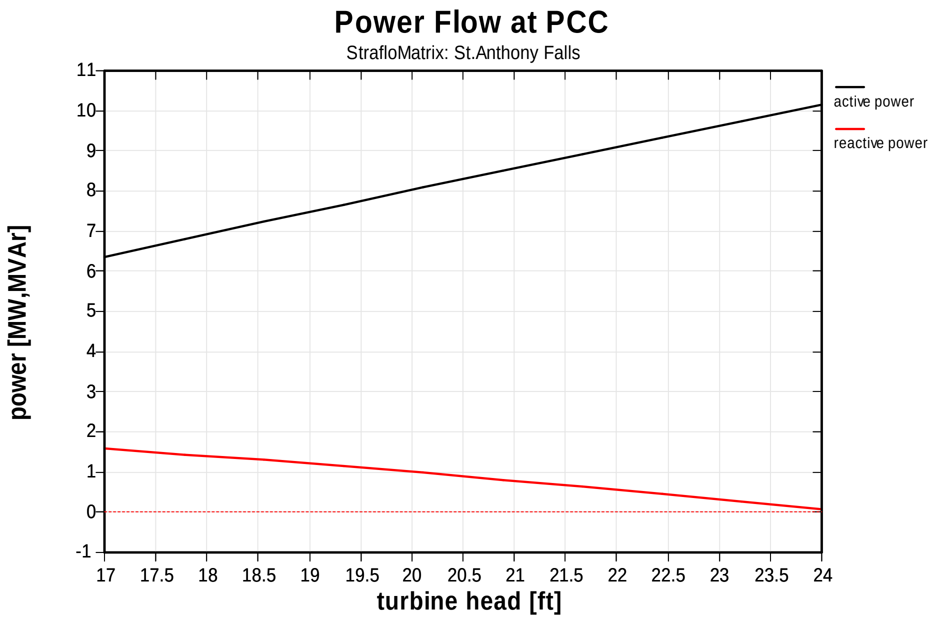
§ Single line diagram Lower St. Anthony Falls



IEEE 1547 - Voltage Regulation

- In general, a PM generator cannot maintain voltage at the point of common coupling (PCC) to the electric power system (EPS).
- Variation of voltage at the PCC will cause a variation of the reactive energy generated by PM generators since that reactive energy directly depends on voltage difference between the PCC voltage and generator internal voltage. This behavior of PM generators also explains how those generators could contribute to voltage regulation at the PCC.



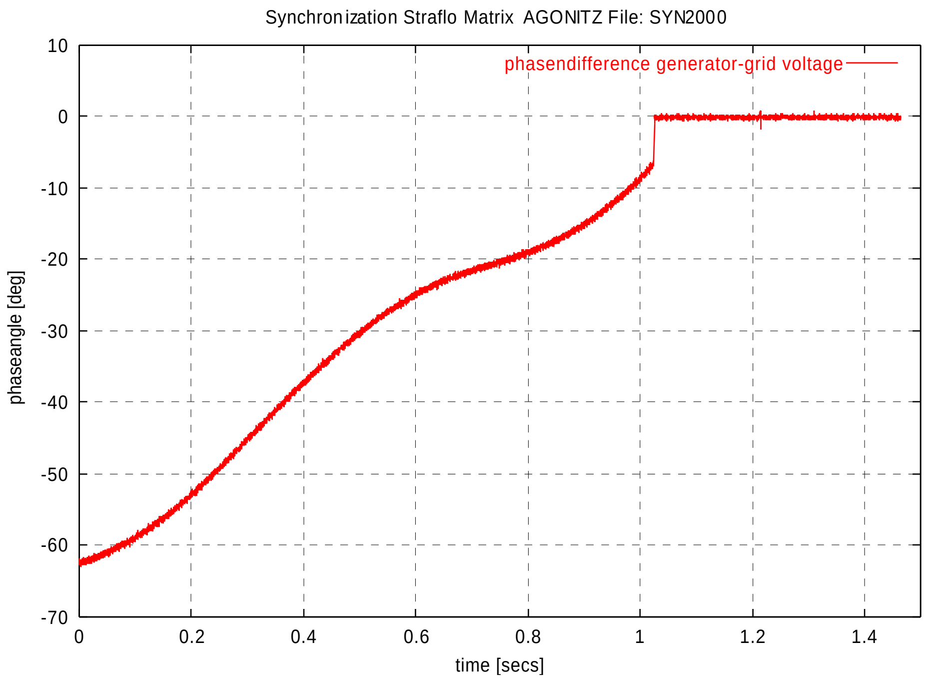


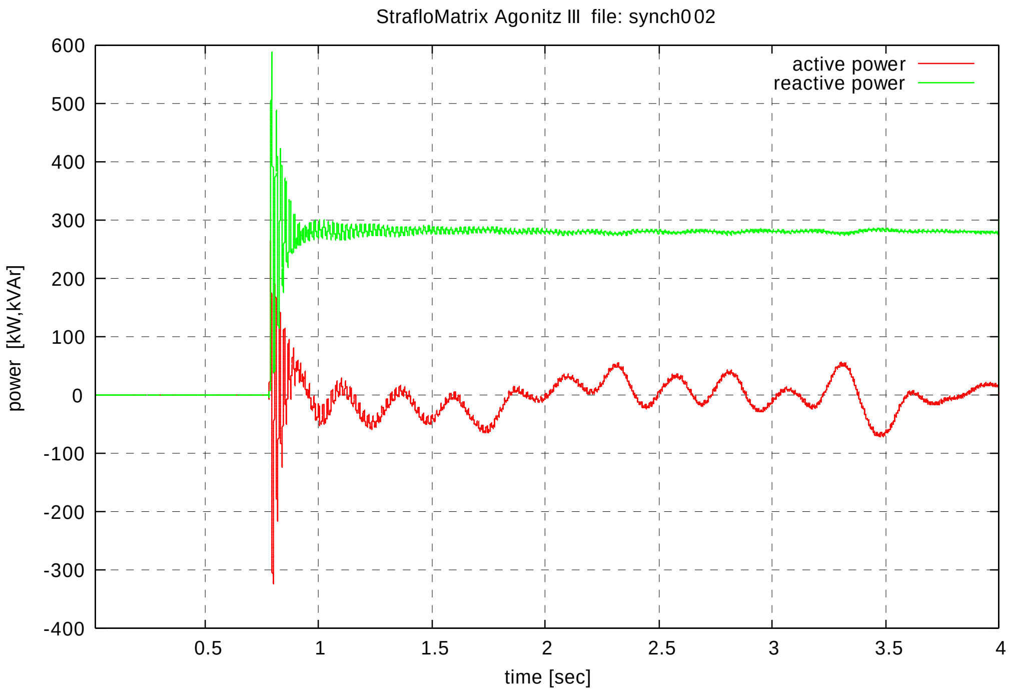
IEEE 1547 - Integration with Area Power System Grounding

- Grounding system is design to prevent overvoltages that exceed the rating of equipment connected to the Area EPS and will not disrupt the coordination of the ground fault protection – IEEE 1547 requirement
- PM generators neutral point is isolated. Since that the 4.16 kV voltage level is ungrounded earth fault current on this level will consist of capacitive currents flowing through capacitive resistance of all equipment connected to the 4.16 kV voltage level to ground. To avoid development of second earth fault on the different place of the 4.16 kV voltage level system a direction earth fault relay will be provided for the each individual PM generator.
- To all other voltage levels grounding methods developed by corresponding standards will be applied.

IEEE 1547 - Synchronization

- The DR unit shall parallel with Area EPS without causing a voltage fluctuation at the PCC greater than ± 5% of prevailing voltage level of the Area EPS at the PCC
- StrafloMatrix™ generators shall be synchronized to the EPS using synch-check function available in multifunctional relays of each PM generator

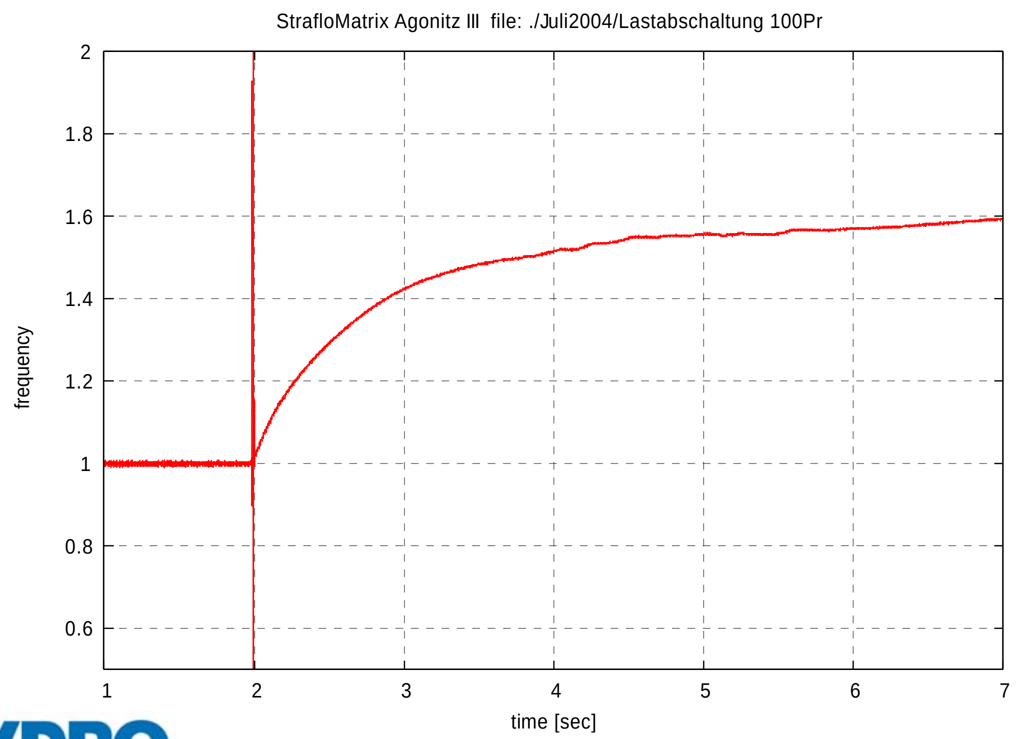




IEEE 1547 – Load Rejection

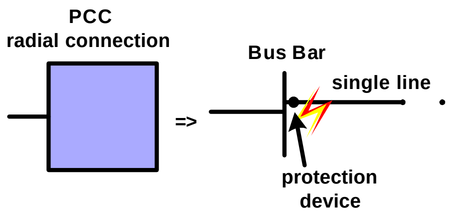
Emergency stop may happen in the following cases:

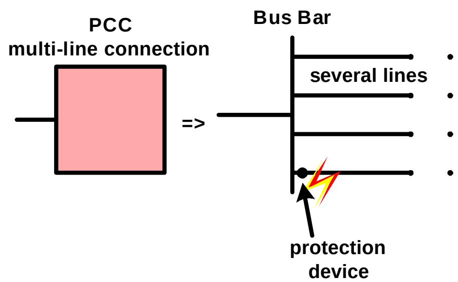
- Fault occurs in the EPS and causes shutdown of all StrafloMatrix™ units connected at the time to the EPS
- Individual protection of PM generators detects a fault
- Manual shutdown of all or individual StrafloMatrix™ unit connected to the EPS due to some detected abnormal unit operating conditions



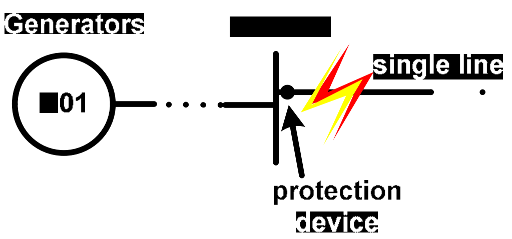
IEEE 1547 – Inadvertent Energizing of the area EPS

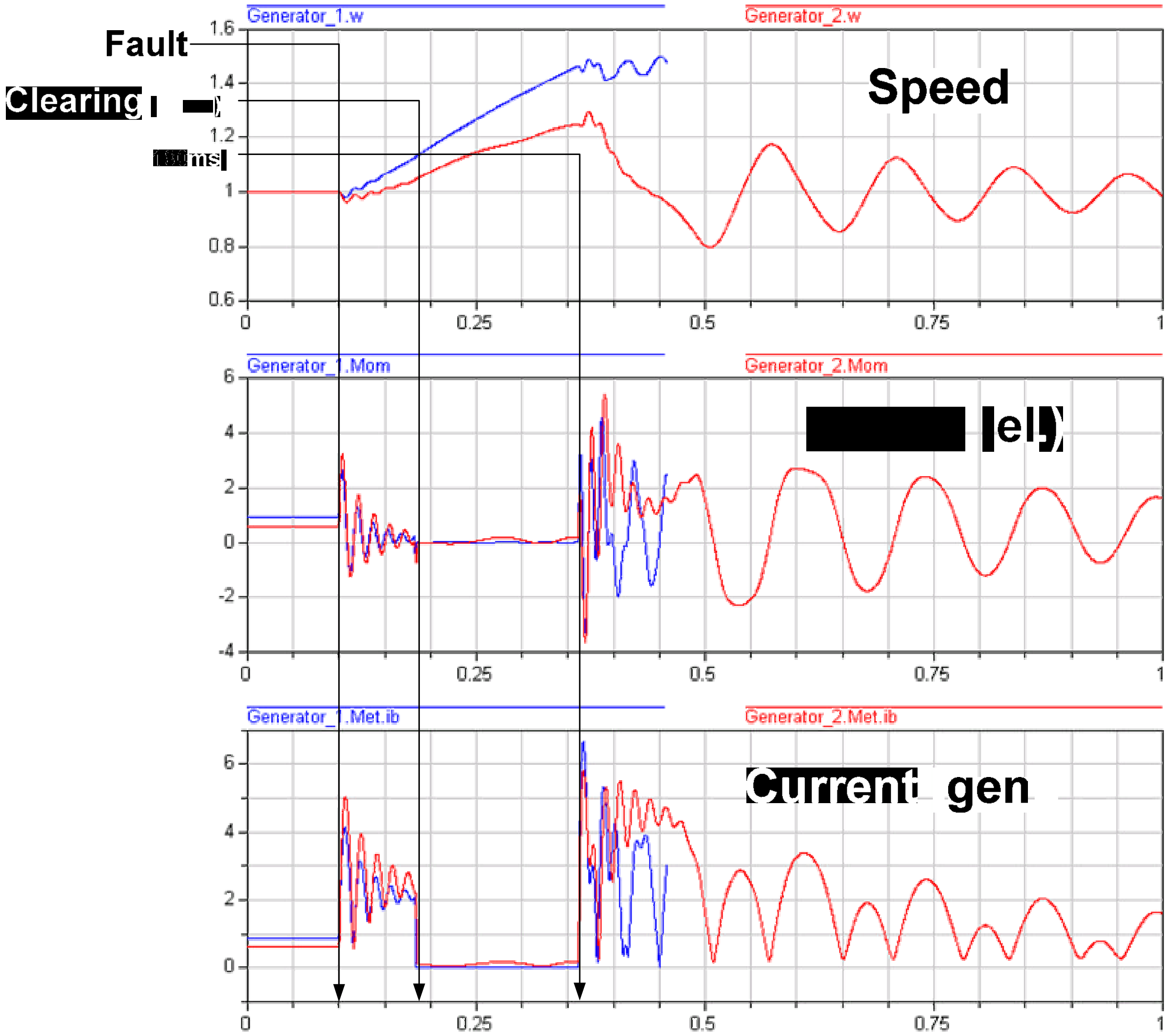
- The DR shall not energize the Area EPS when the Area EPS is de-energized for any reason – IEEE 1457 requirement
- With disconnecting switches that can be locked while maintenance is performed on the system is ensure security for workers beyond the PCC during the maintenance works of Area EPS
- Direct Transfer Trip (DTT) can be used to provide a remote signal tripping the 4.16 kV main circuit breaker when the fault is detected in the protected line section
- This case has been analyzed for different schemes of StrafloMatrix™ units connection to the Area PCC as shown on the following scheme
    - Radial Connection
        - Tripping of faulty line causes complete separation from the system.
    - Multi-line Connection
        - After tripping of faulty line, the plant is still connected to the System through several lines.





IEEE 1547 – 3 phase Fault PCC Radial Connection

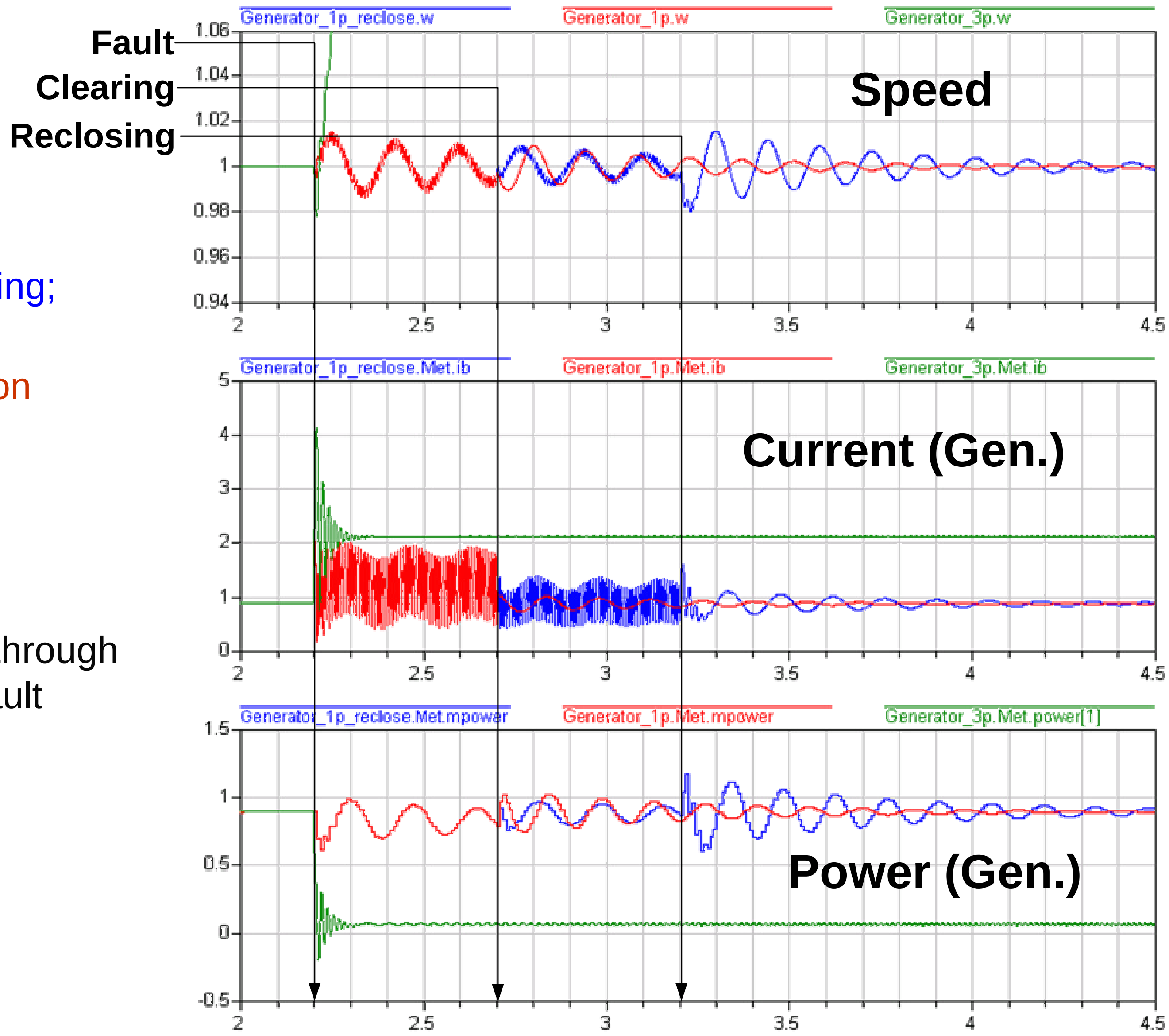




Blue: 16 turbines at maximum head

Red: 1 turbine at minimum head

IEEE 1547 – 1 phase Fault PCC Radial/Multi-line Connection



Blue: Radial connection; Single-Phase tripping; Reconnection

Red: Multi-line connection

Green: 3-Phase Fault (not cleared)

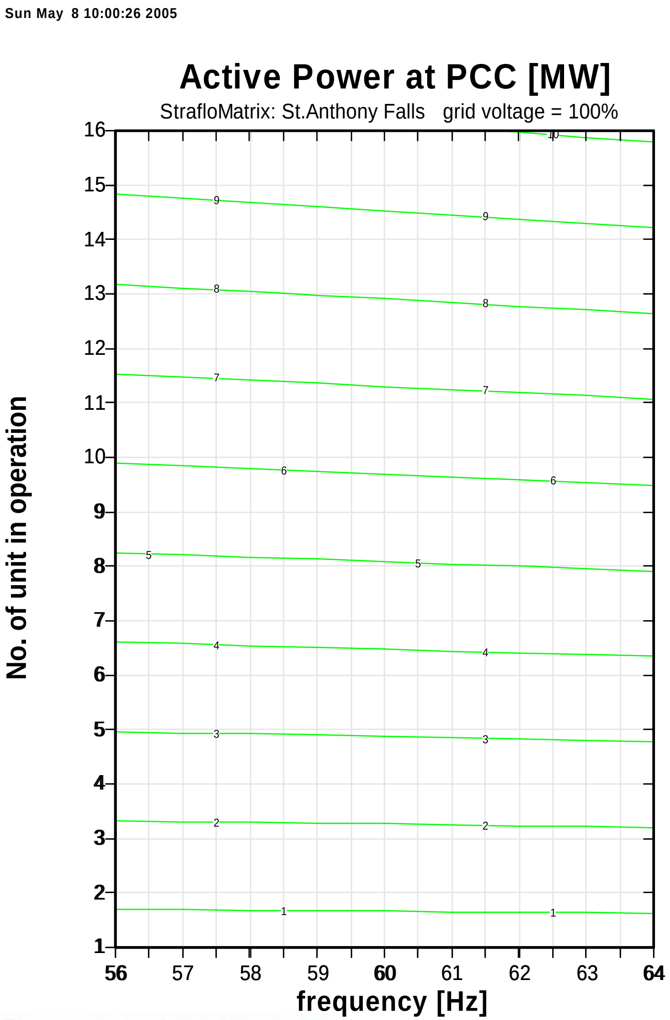
Results:

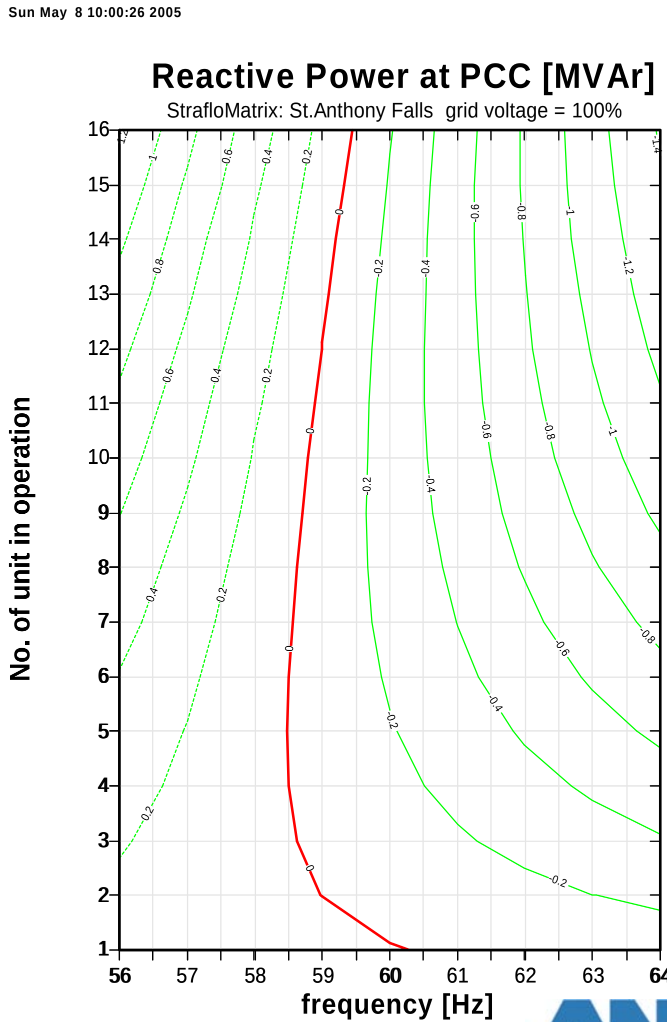
Power can be transported through 2 phases even during the fault

Stable operation is possible

IEEE 1547 – Response to Area EPS Abnormal Frequency

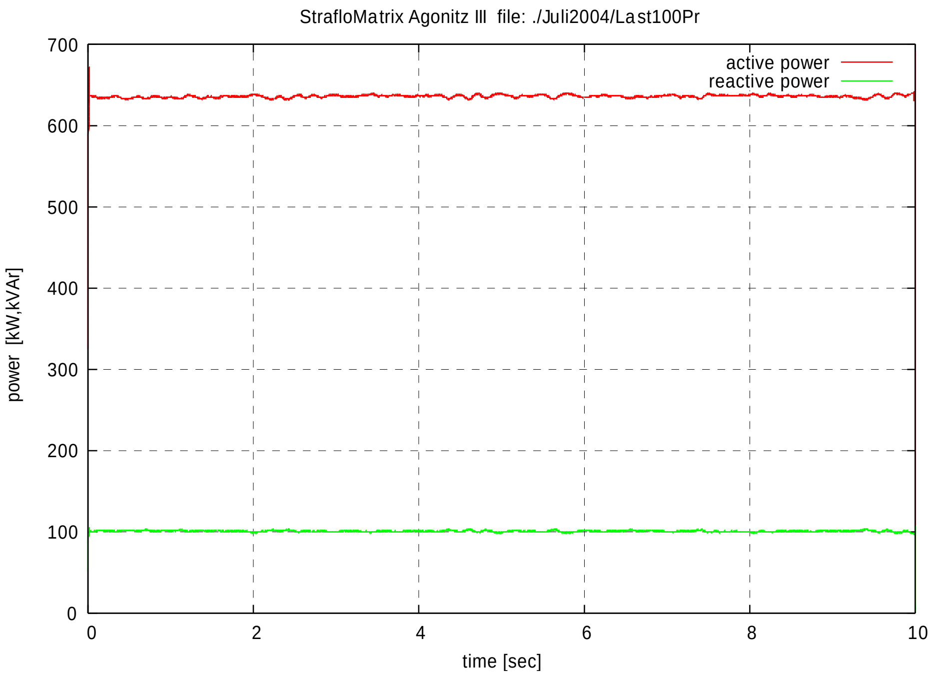
- Regulation of frequency during operation to the EPS StrafloMatrix™ units are not equipped with a governing regulator therefore StrafloMatrix™ units are not designed for island operation.
- In addition, PM generator active and reactive power will change if frequency of the EPS varies

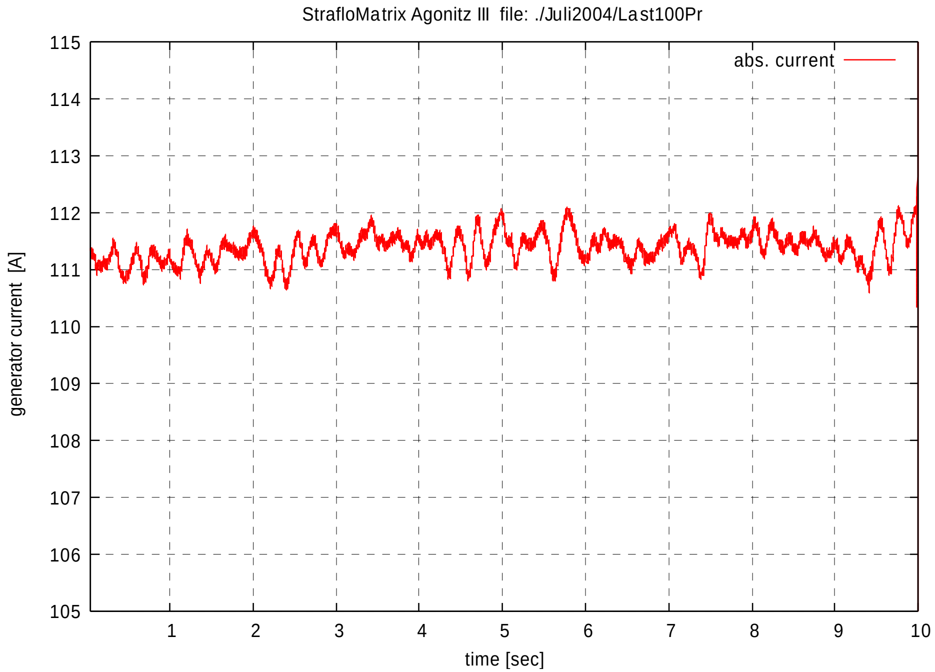




IEEE 1547 – Response to Area EPS Abnormal Conditions: Limitation of Flicker Induced by the DR

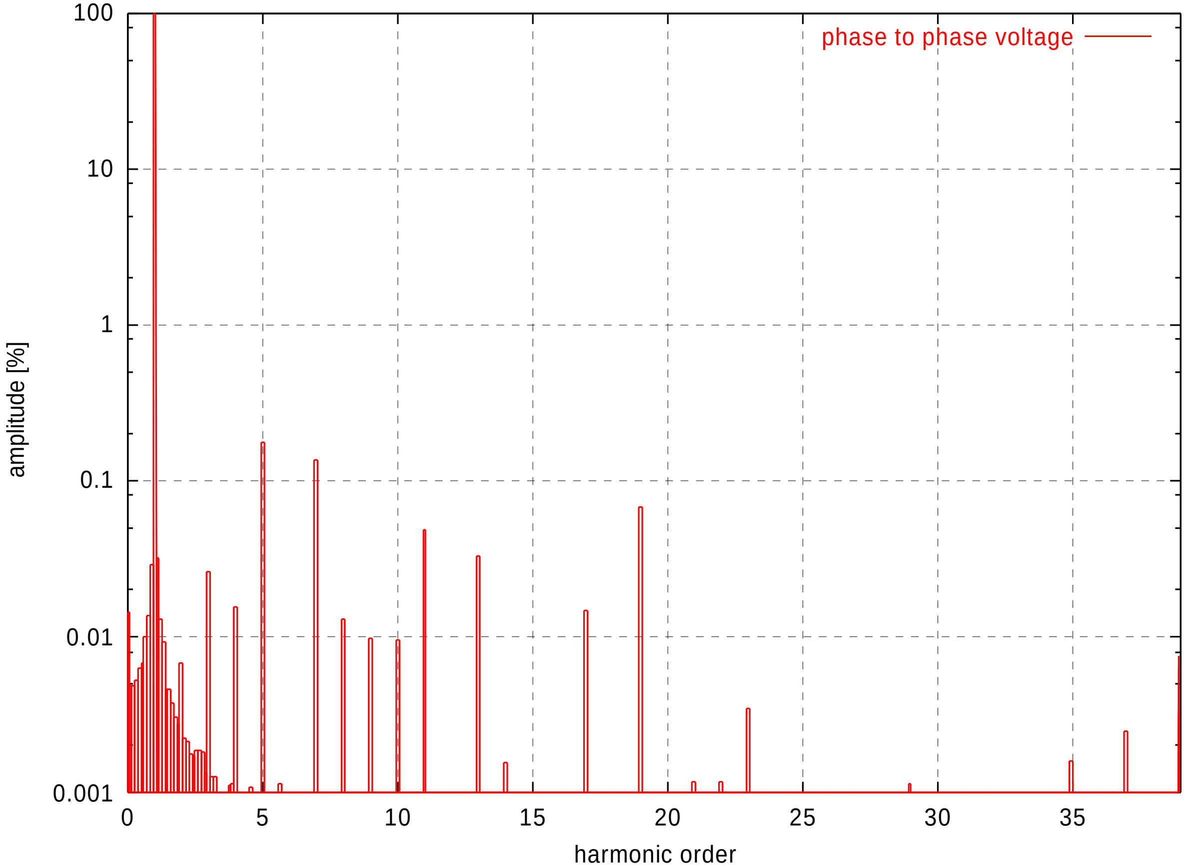
- Taking the possible operation regime of StrafloMatrix units into account, we have assumed 1 or 2 start/stops per day. The allowable percentage voltage DIP for this scenario according to the Xcel Energy´s regulations is 4%. The StrafloMatrix™ units will fulfill this requirement
- Step changes of the StrafloMatrix™ unit output are not possible (unregulated units)





IEEE 1547 – Response to Area EPS Abnormal Conditions: Harmonics

A low level of harmonic content in PM generator induced voltage is shown and is in accordance to IEEE 1547 requirement



IEEE 1547 – other requirements

- Monitoring Provisions

  Any request either from IEEE 1547 or some local utility organization regarding provisions for monitoring DR unit connection status

- Isolation Device

  Readily accessible, lockable, visible-break isolation device located between the Area EPS and DR unit

- Protection from Electromagnetic Interference

  The multifunction protection relays planned to be used for this project will fulfill condition referring to protection from Electromagnetic Interference as specified in IEEE 1547 requirement

- Surge Withstand Performance

  Switching over voltages at the 4.16 kV equipment can not be analyzed accurately with a simple model. Nevertheless the investigations showed that over voltages at the StrafloMatrix™ generator after opening of the generator contactor are likely to have the highest values

- Paralleling Device

  The interconnection system paralleling-device shall be capable of withstanding 220% of the interconnection system rated voltage, IEEE 1547 requirement

IEEE 1547 – other requirements

- Response to Area EPS Abnormal Conditions: Area EPS Faults

  The Lower St. Anthony Falls DR equipment is designed considering that "the combined available fault current" on the 13.8 kV voltage level will be 250 MVA as defined in standards for this voltage level

- Response to Area EPS Abnormal Conditions: Area EPS Reclosing Coordination

  In accordance with IEEE requirements the Lower St. Anthony Falls units will be disconnected from the EPS as soon as a temporary fault condition occurs in the Area EPS

- Response to Area EPS Abnormal Conditions: Loss of Synchronism

  Any separation from the main section of the Area EPS will bring units to a shutdown position. Reconnection to the Area EPS will be done as outlined in the chapter Synchronization

References

/1/ www.hydromatrix.at

/2/ VA TECH HYDRO: HYDROMATRIX®– Product Information

/3/ Volker Kienberger-, Harald Schmid, VA TECH HYDRO GmbH & Co, Austria and Hans Schimpf, VERBUND-Austrian Hydro Power AG, Austria, Hydro Vision 2006, Portland USA

/4/ William D. Stevenson, Jr. Element of Power System Analyses

/5/ Prabha Kundur, Power System Stability and Control, McGraw Hill 1994

/6/ Univ.-Prof.Dr.-Ing Guenther Brauner, DI Martin Heidl, Vienna University of Technology: Grid Integration of StrafloMatrix™ - Generators (Lower St. Anthony Falls)

/7/ Cigre, July 2003 : Development of Dispersed generation and Consequences for Power System

/8/ CIRED; Report of Working Group No. 4 on Dispersed generation

/9/ MIT Open Courseware ocw.mit.edu

/10/ IEEE standard 1547: Standard for Interconnecting Distributed Resources with Electric Power Systems

Authors

- **Nesha Danilovic**, DI, is a member of Engineering Services of VA TECH HYDRO GmbH, Vienna, Austria. Graduated at the Electrotechnical University of Belgrade he works about 20 years as a consultant in a field of hydro power plant design in Serbia and Canada before he joined VA TECH HYDRO in 1999. He is also registered Professional Engineer in Canada.
  mailto:Nesha.Danilovic@vatech-hydro.at

- **Johann Hell**, DI, is a member of Generator Hydro Engineering Tenders of VA TECH HYDRO GmbH, Vienna, Austria. Graduated at the Vienna University of Technology he works about 15 years in the field of Sales and R&D for variable speed drives and frequency converters. Since 1999 he is project engineer for generator tenders.
  mailto:Johann.Hell@vatech-hydro.at