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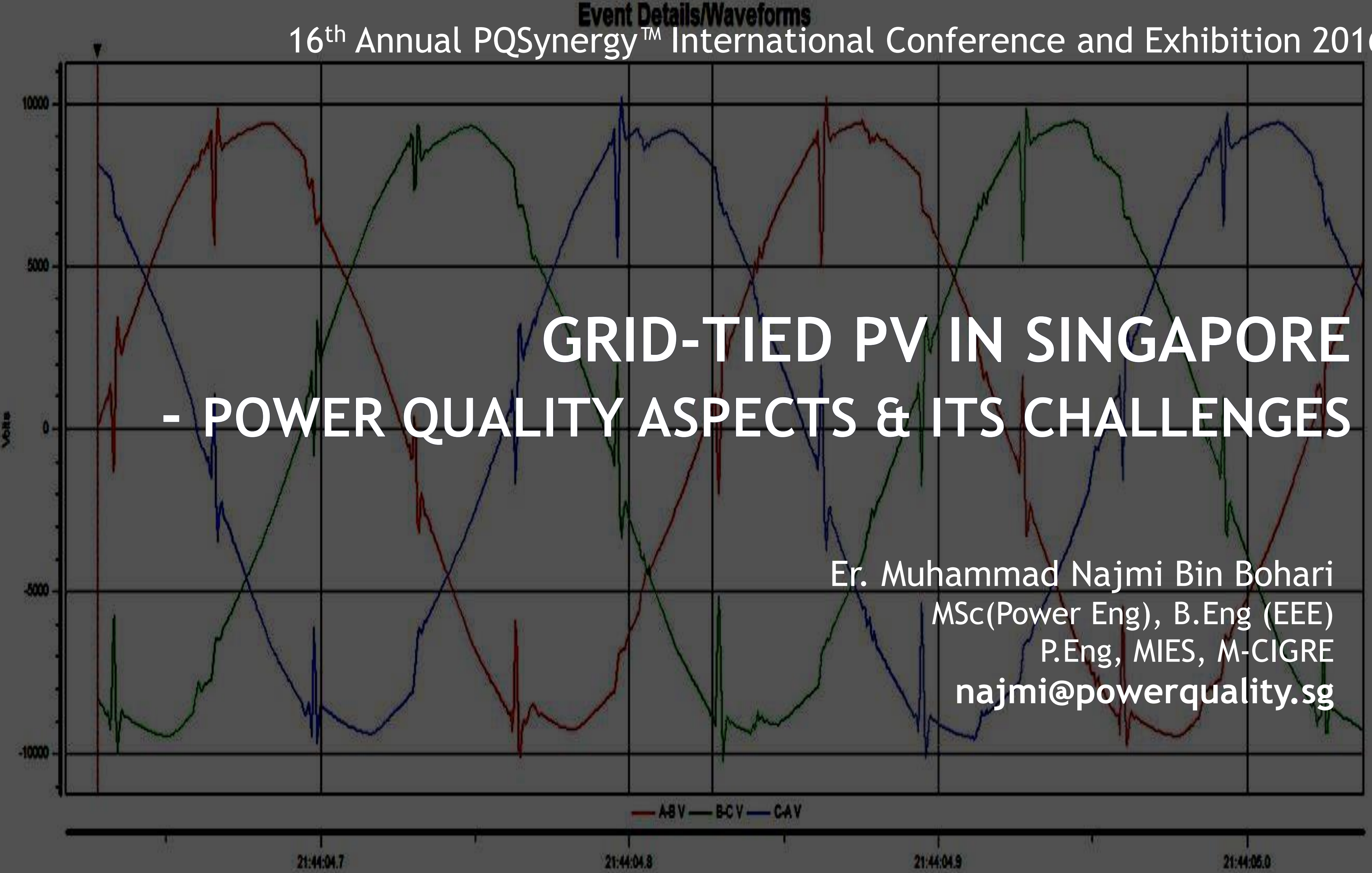

GRID-TIED PV IN SINGAPORE
- POWER QUALITY ASPECTS & ITS CHALLENGES

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HELLO. I AM NAJMI

- Professional Engineer (Singapore).
- Current area of practice:
  commissioning of grid-tied solar pv,
  power quality analysis, protection coordination studies and assessment of electrical earthing & lightning protection systems.
- Formerly from SP PowerGrid's Power Quality & Transient Management section.
- Writes on http://powerquality.sg, to share my views and experiences in this fascinating world of power quality.

OUTLINE

- Power Generation in Singapore
- Introduction to Grid-Tied PV in Singapore
- Sharing of Experience on Past Assessment of PQ Impacts
- Take-aways & Challenges

POWER GENERATION IN SG

- Total Licensed Generation Capacity of 13404.7 MW (1Q 2016)
- Total Grid-Tied PV Output = 455.6MW (1Q 2016)

Plant Technology Share of Electricity Generation, 2008 - 2014

Unit: Percent (%)

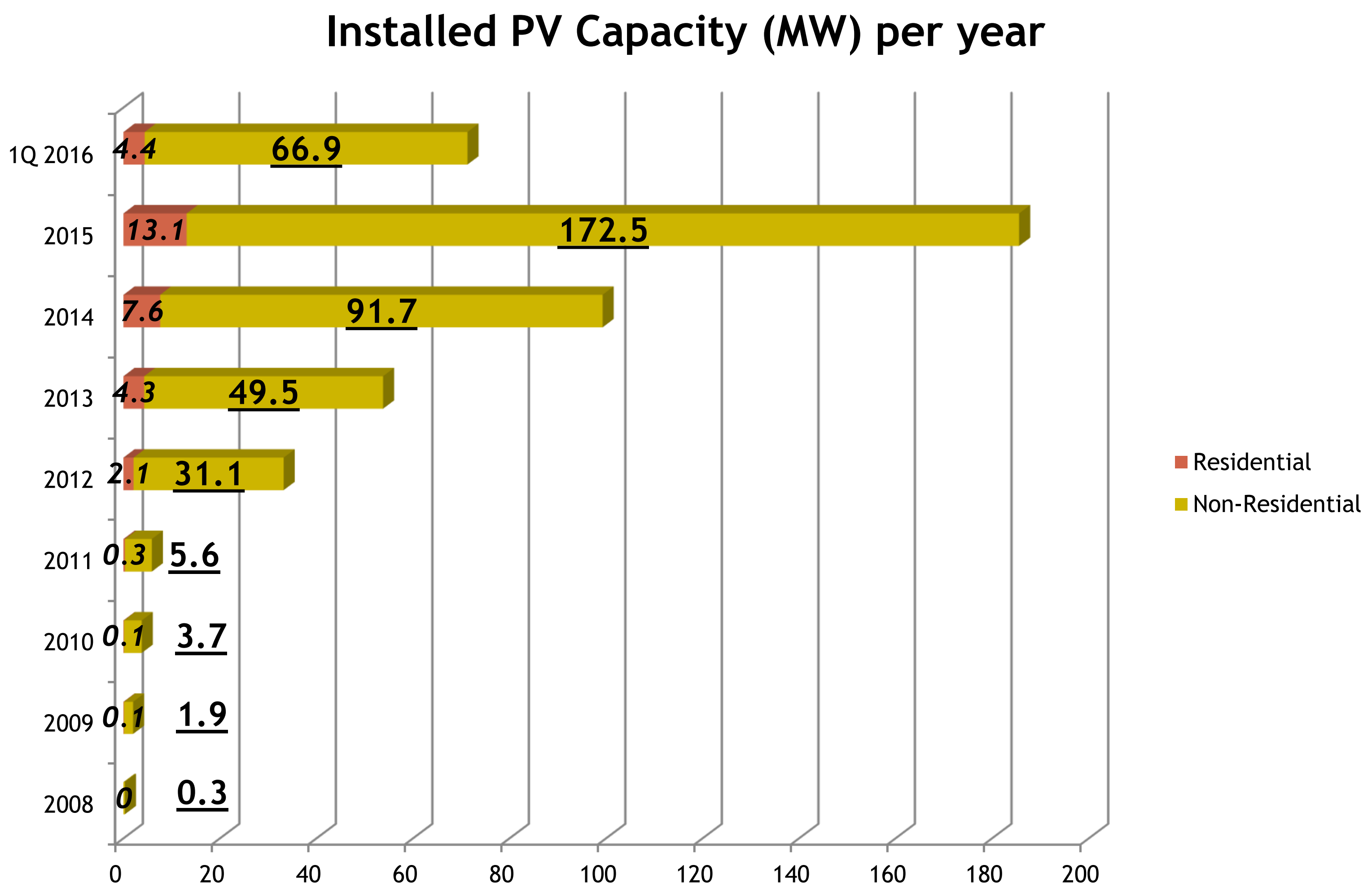
	2008	2009	2010	2011	2012	2013	2014
CCGT/Co-Gen/Tri-Gen	82.0	82.0	80.0	82.0	86.8	93.8	97.4
Steam Turbines	16.0	16.0	17.0	16.0	10.5	3.6	0.0
Others	2.0	2.0	3.0	2.0	2.7	2.6	2.6

Source: Energy Market Authority (EMA)

Note:
a. Numbers may not add up to the totals due to rounding.

Last updated on 6 Jul 2015

INSTALLED GRID-TIED PV MWP



Source: EMA / SP PowerGrid

GRID-TIED PV IN SINGAPORE

- Singapore is a small city-state
- Virtually no land space for big solar farms
- Absence of feed-in tariffs
- Direct ownership and Solar-leasing are two main models here in Singapore
- PV System connected at low-voltage inside Customer's premises

POSSIBLE AREAS FOR PV IN SG

Table 4.1: Overview of possible areas for PV installations in Singapore, based on the discussion above.

Space type	Area used	Total area (km^2)	Area utilisation factor[1]	Net-usable area (km^2)
Roof-top[1)]	HDB blocks	14	0.5[2)]	7
	Other buildings	42	0.6[3)]	27
Facades[1)]	Top-5 stories	10	0.40	4
Infrastructure	MRT tracks	0.5	1.00	0.5
Islets	Ground-mounted	50	0.05	2.5
Inland waters	Floating PV (mainland only)	20	0.20	4
TOTAL				**45**

1) based on existing building stock in 2011, and conservatively projecting the same building stock for the timeframe under consideration in this roadmap.
2) based on the lowest value for possible un-shaded installations on HDB blocks from studies at NUS [Won]
3) based on the lowest value for possible un-shaded installations on other buildings from studies at NUS [Won]

Source: Solar PV Roadmap for Singapore by SERIS

PUBLIC HOUSING ROOFTOPS

PUBLIC HOUSING ROOFTOPS

PRIVATE HOUSING

Source: Rezeca Renewables

INSTITUTIONS

FACTORIES

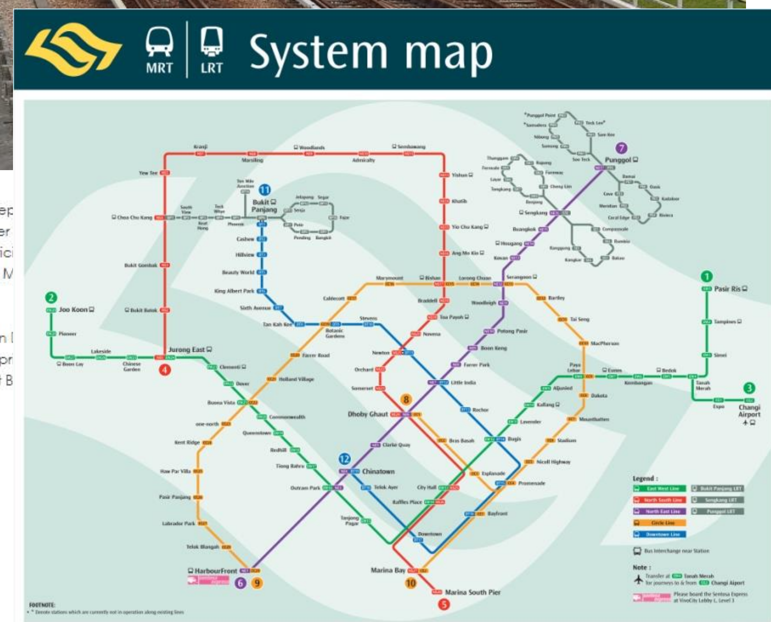
Source: Rezeca Renewables

FLOATING PV

Source: Phoenix Solar

MRT DEPOT & TRACKS?

SMRT's Bishan Depot to be Powered by Solar Energy



SMRT Trains Ltd, Singapore's largest rail operator, announced today a partnership with Sunseap Leasing Pte Ltd, Sing energy provider, which will allow SMRT's Bishan Depot to run on renewable solar energy by the end of this year. The deal at Bishan Depot, Singapore's first and largest rail depot, will see a pilot 1 MegaWatt-peak (MWp) solar pho within the depot's premise, a system capable of meeting the depot's operational energy needs[1] .

Covering an initial area of about 10,000 square metres, the solar PV system will be installed on the rooftop of Bishan Depot's Main Dep Installation of the PV system will commence in the third quarter of this year and is expected to be operational at the end of October allow SMRT to reduce its carbon footprint by 553 tonnes of CO_2 annually. Under optimal conditions, the system can generate electrici the annual energy consumption of about 270 four-room HDB flats. The system in Bishan Depot may be extended to provide up to 5 M the successful completion of the pilot trial.

Mr Ng Bor Kiat, SMRT Senior Vice President for Systems and Technology, said, "The installation of a solar photovoltaic system at Bishan SMRT's first application of solar technology in our facilities. It will allow us to diversify our energy sources and reduce the carbon footpr expanding trains operations. We are optimistic about expanding the system to generate up to 5 MWp, maximising solar potential at B Depot."

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DYNAMIC PATHWAY APPROACH

- To manage intermittency by procuring sufficient reserves in tandem with the growth of IGS
- 600MWac is the first threshold (does not constitute as a cap)

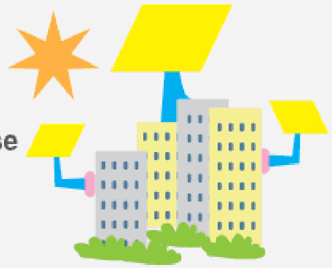
SOLARNOVA

- Government-led demand to install 350MWp, or 5% of Singapore's current peak power consumption of solar energy capacity by 2020
- Government-sites and public housing blocks

INCREASING RENEWABLE ENERGY USE

As a step towards reducing our reliance on imported fuel and carbon footprint, we will do more to encourage the use of renewable energy.

The Government will work with agencies to catalyse
SOLAR DEPLOYMENT



The Government plans to raise the adoption of solar power in our system to 350 Mega-Watt-peak (MWp) by 2020. Economic Development Board (EDB) will work with key agencies to aggregate solar demand across government buildings and spaces under the 'SolarNova' programme. This will demonstrate the viability of solar energy in Singapore and catalyse the growth of the clean-energy sector across the value chain. It will also create opportunities for Singapore businesses.

As renewable energy sources are intermittent by nature, the Energy Market Authority (EMA) is **reviewing its regulatory framework** to ensure system stability, even with greater adoption of renewables. The solar industry has welcomed EMA's proposals to increase the threshold for intermittent generation sources and streamline market registration procedures. EMA will continue to work with the industry to refine its regulatory framework.

We will continue to support the increased use of renewables. Through the Energy Innovation Programme Office, we will fund research into energy management technologies to facilitate the integration of renewable energy into our electricity grid.

CONNECTION BRIEFS

- Wiring regulations and installation to follow local code of practice (modified of BS7671)
- Submission to Utility company (SP PowerGrid)
  - to be submitted by Licensed Electrical Worker
  - inverter specifications
  - inverter test reports (PQ, Loss of Mains)
  - power quality compliance report (complexity varies on size of PV)
  - single-line diagram
  - pre / post 7-day PQ measurement (>1MWac)
- 1 minute interval kW data to power system operator (>100kWac)

INFORMATION ON SOLAR PV

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Overview of Solar Development in Singapore

Solar energy remains the most promising renewable energy source for Singapore when it comes to electricity generation. With an average annual solar irradiance of 1,150 kWh/m2/year and about 50 percent more solar radiation than temperate countries, solar photovoltaic (PV) generation has the greatest potential for wider deployment in Singapore. The latest statistics on solar PV in Singapore can be found here.

Deployment of solar energy brings about several benefits to Singapore:

- Solar energy generates no emissions, which contributes to environmental sustainability.
- Solar energy requires no import of fuels, which in turn enhances Singapore's energy security.
- Solar energy can reduce peak demand. This is because the peak energy usage in Singapore – typically in the afternoons – coincides with the periods when solar energy can be maximised. So lowering peak demand can potentially reduce electricity pool prices and bring benefits to consumers.

However, there are two limitations to deploying solar energy on a large scale to generate electricity reliably:

- Singapore's small physical size, high population density and land scarcity limit the amount of available space to deploy solar energy.
- Any power system with significant penetration of solar energy for electricity generation must manage intermittency appropriately, so as not to compromise grid stability.

Managing Intermittency

The output of solar PV is variable and dependent on weather conditions as compared with a conventional generator that produces a stable output. So output from solar is largely dependent on environmental factors and weather conditions such as the amount of sunlight, cloud cover and shadow. This can result in imbalances between supply and demand.

For example, a moving cloud can cause a sudden drop in solar energy output, which means conventional generators need to be on standby to make up for the shortfall. Failure to do so can result in blackouts. As such, the power system operator needs to ensure that there are sufficient back-up reserves of conventional generators available to cater for these changes.

INFORMATION ON SOLAR PV

SINGAPORE POWER

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Power Quality

SP PowerGrid has built one of the world's best electricity and gas networks to power the Singapore economy. Singapore today has one of the fewest and shortest electricity outages of cities worldwide. Supply interruptions are few and their durations brief.

Today, SP PowerGrid proactively focuses on power quality to better serve the needs of the high-technology manufacturing and process industries such as wafer-fabrication, pharmaceutical and petrochemical plants.

A Power Quality section, set up in 1998, underpins SP PowerGrid's commitment to support the growth of key industries by working closely with them to help them achieve optimal power quality. The section studies state-of-the-art power quality technologies that can provide performance improvements and monitors power quality performance across the system.

Power Quality Monitoring Centre

The Power Quality Monitoring Centre tracks power quality data, including the magnitude and duration of voltage dips. It analyses power quality performance and works to achieve improvements or mitigations through the network or at the customer's plant. It does this by measuring and analysing the dip levels and frequencies in different parts of Singapore.

Customers can use the data to make informed decisions on the degree of equipment hardening necessary. For new customers, the data would help them to better select equipment specifications, plant design and power conditioning options to ride through voltage dips.

Condition Monitoring Programme

Another major effort in improving power quality is condition monitoring, which detects and removes incipient faults in the network. This averts network failures which could cause voltage dips.

The condition monitoring systems include partial discharge detection, thermal scanning, SF6 gas quality checks and dissolved gas analysis.

2008 to 2013

PAST EARLY PQ ASSESSMENTS

- Low voltage (LV) networks of the Utility Grid
- Measurements at the Point of Common Coupling (at Utility side)
- Based on existing voltage-based Grid PQ requirements
- Voltage Harmonics
- Voltage Fluctuation/Flicker
- DC Injection

TYPICAL LV NETWORK

- 400V 3 phase / 230V 1 phase
- Served by a 1MVA or 1.5MVA oil filled transformer
- Short-circuit rated capacity of 36kA / 43kA
- Radial networks

TYPICAL LV NETWORK

Transformer

LV Board

Overground Box

Customer's Premises

HARMONICS

- To ensure that Customer's generated current harmonics will not result in voltage harmonics at the point of connection to exceed the prescribed limits

	Description	Limits		
1)	**Harmonics**			
		230/400 V	**6.6/22 kV**	**66 kV**
	Total harmonic voltage distortion, V_{THD}	5%	4%	3%
	Individual harmonic voltage (odd)	4%	3%	2%
	Individual harmonic voltage (even)	2%	2%	1%

VOLTAGE HARMONICS

- Being a voltage-based requirement, it is possible for any quality of PV inverters to be connected
- Hence each connection application are also assessed to ensure each inverter meets the relevant product standards
- Eg. IEC 61000-3-2, IEC 61000-3-12
- Limit for emission of harmonic current

HARMONICS

- The expected voltage harmonics was calculated using the formula prescribed in U.K Engineering Recommendation G5/4, with consideration of existing voltage harmonics present (from measurement)

G5/4 Prediction of Voltage Harmonics

Site: 5
Measured from 15/03/2016 15:41:30.0 to 15/03/2016 16:12:32.0
SUPPLY SYSTEM VOLTAGE: 400 V

	New Load		Measured Vh(%)			Total Vh(%)		
	Ih(Amps)	Pred. Vh(%)	CHA	CHB	CHC	CHA	CHB	CHC
H02	2.00	0.03	0.11	0.10	0.11	0.13	0.13	0.14
H03	1.71	0.04	0.49	0.58	0.62	0.52	0.61	0.66
H04	1.25	0.03	0.08	0.05	0.04	0.11	0.09	0.07
H05	3.42	0.12	1.34	1.14	1.43	1.46	1.26	1.54
H06	0.20	0.01	0.04	0.05	0.02	0.04	0.05	0.02
H07	2.31	0.11	0.64	0.71	0.51	0.65	0.72	0.52
H08	0.51	0.01	0.05	0.05	0.03	0.05	0.05	0.04
H09	0.52	0.02	0.92	0.78	0.94	0.93	0.80	0.95
H10	0.51	0.02	0.05	0.04	0.02	0.06	0.04	0.03
H11	0.97	0.04	0.47	0.20	0.34	0.47	0.21	0.34
H12	0.13	0.01	0.04	0.03	0.02	0.04	0.03	0.02
H13	0.62	0.03	0.82	0.38	0.71	0.82	0.38	0.72
H14	0.37	0.02	0.03	0.03	0.02	0.03	0.03	0.03
H15	0.11	0.01	0.78	0.44	0.86	0.79	0.45	0.87
H16	0.20	0.01	0.03	0.02	0.02	0.03	0.02	0.02
H17	0.07	0.00	0.70	0.45	0.75	0.70	0.45	0.75
H18	0.06	0.00	0.04	0.03	0.02	0.04	0.03	0.02
H19	0.06	0.00	0.68	0.65	0.54	0.68	0.65	0.54
H20	0.08	0.01	0.03	0.04	0.01	0.03	0.04	0.02
H21	0.04	0.00	0.24	0.28	0.33	0.24	0.29	0.34
H22	0.06	0.00	0.04	0.04	0.01	0.04	0.04	0.01
H23	0.04	0.00	0.43	0.59	0.31	0.43	0.59	0.31
H24	0.03	0.00	0.03	0.05	0.02	0.03	0.05	0.02
H25	0.04	0.00	0.26	0.43	0.34	0.26	0.43	0.34
H26	0.03	0.00	0.02	0.05	0.01	0.02	0.05	0.01
H27	0.02	0.00	0.09	0.25	0.11	0.09	0.25	0.11
H28	0.03	0.00	0.02	0.04	0.01	0.02	0.04	0.02
H29	0.04	0.00	0.29	0.60	0.17	0.29	0.60	0.17
H30	0.01	0.00	0.02	0.03	0.01	0.02	0.03	0.01
H31	0.04	0.00	0.12	0.37	0.27	0.12	0.37	0.27
H32	0.03	0.00	0.01	0.03	0.01	0.01	0.03	0.01
H33	0.02	0.00	0.08	0.13	0.12	0.08	0.13	0.13
H34	0.03	0.00	0.01	0.02	0.01	0.01	0.02	0.01
H35	0.02	0.00	0.17	0.38	0.11	0.17	0.38	0.11
H36	0.01	0.00	0.02	0.02	0.02	0.02	0.02	0.02
H37	0.01	0.00	0.08	0.27	0.32	0.08	0.27	0.32
H38	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01
H39	0.01	0.00	0.06	0.08	0.20	0.07	0.08	0.20
H40	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01
						0.12	0.26	0.14
						0.01	0.01	0.01
						0.06	0.13	0.23
						0.01	0.01	0.01
						0.05	0.06	0.18
						0.01	0.01	0.01
						0.06	0.18	0.11
						0.01	0.01	0.01
						0.04	0.05	0.19
						0.01	0.01	0.01
Total VTHD(%)						2.59	2.39	2.65

Non-Linear Load:
Add-on of 7 x 30kWac inverters

HARMONICS

- Measurement consisted of both day and night time trends
- Harmonic levels showed no dependency on the power generated from the inverters
- Levels were actually higher at night when inverters are not in operation
- Harmonic levels in day time period, before and after the installation of the inverters stayed relatively the same

BEFORE/AFTER VTHD

	Transformer / PV Size	Measured VTHD% (Pre)	Expected VTHD%	Measured VTHD% (Post)
1	PCB162TF1 1.5MVA /192kW	1.87	2.27	1.95
2	PCB162TF2 1MVA /96kW	1.58	1.89	1.75
3	PCB166TF1 1MVA / 144kW	1.76	2.15	1.77
4	PCB166TF2 1MVA / 144kW	1.77	2.11	1.85
5	EPB171TF1 1.5MVA / 105.6kW	1.99	2.06	1.94
6	EPB172TF1 1.5MVA / 158.4kW	1.64	1.92	1.64
7	PDB637TF1 1.5MVA /82.56kW	1.83	2.07	2.2
8	PDB637TF2 1MVA / 88.32kW	1.98	2.27	1.80
9	PDB641TF1 1.5MVA / 87.36kW	1.91	2.19	1.76
10	PDB641TF2 1.5MVA / 48kW	1.86	2.17	1.85
11	EDPB119N1TF1 1MVA / 215kW	2.05	2.41	2.11
12	EDPB119N1TF2 1MVA / 120kW	1.78	2.06	1.89
13	EPB180N1TF1 1.5MVA /268.8kW	2.02	2.52	2.23
14	EPB180N2TF1 1.5MVA /132.5kW	2.12	2.55	2.10
15	EPB180N2TF2 1MVA / 112.3kW	1.93	2.35	1.98
16	EPB119N2TF1 1MVA /60kW	1.75	2.01	1.83

FLUCTUATION & PV

- To ensure that the voltage changes here (associated with the energizing, switching and disconnection of the Grid-Tied PV) must not cause voltage step changes of more than 3% at PCC.
- This includes the fluctuating nature of PV power output
- And maintain flicker limits within
  Pst=1.0
  Plt=0.8

VOLTAGE FLUCTUATION

- Voltage fluctuation are linked to the size of the equipment.
- Highly dependent on magnitude of system impedance (“Stiffness ratio”).
- Traditionally as a result of starting a machine (induction generator / motor / or energizing a direct-connected synchronous generator)

FLICKER & PV

- **IEC TR61000-3-15**: For DG equipment of limited power and exporting into public supply at a high short circuit current connection, it is unlikely that the DG will introduce noticeable flicker.
- **IEEE 1547**: The PV power source, although not a constant, is generally slow to change relative to the change rates involving flicker. It had been a concern that cloud-irradiance changes could produce objectionable flicker. However at this moment, data show no flicker is encountered from cloud-caused irradiance.

FLICKER & PV

- The statements made matched my own observation /experience in conducting pre and post measurements for these Grid-Tied PV-Solar connection (so far).

PRODUCT STANDARDS

- **IEC 61000-3-3 / 11**: Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems.
- Intended to apply for low impedance connections having a high short circuit current capability.
- The contribution to Pst and Dmax (maximum voltage change) are the most important parameters when DG equipment exports power to Grid.

PRODUCT STANDARDS

- In E.R P28, equipment meeting the BS5406 Part 3 – Disturbances in supply systems caused by household appliances and similar equipment: Specification of voltage fluctuations (now IEC 61000-3-3) are allowed connection without further assessment

E.R P28

- It further adds that equipment that does not come under BS5406-Part 3 will be assessed under Stage 2
- In Stage 2, individual equipment which cause a short term flicker severity Pst (less or equal to 0.5) can be connected without further assessment

DC INJECTION

- To ensure that Customer PV System's generated total DC injection do not exceed 20mA under normal operating condition
- DC injection into 6.6kV/22kV/66kV networks is deprecated (i.e not allowed)

SOME KNOWN EFFECTS

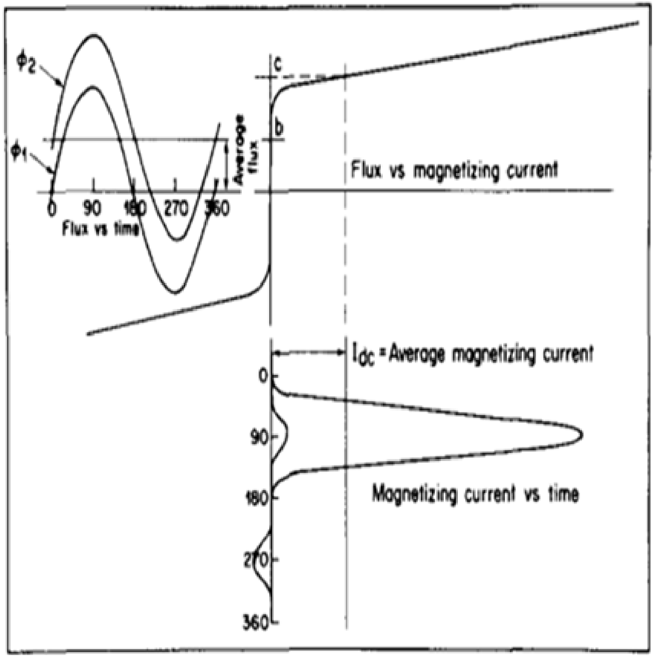

Fig. 3. Effect of direct current on transformer saturation and relation between flux and magnetizing current.

Known Effects of DC Injection

- Cause offset in AC voltage
- Cause transformer saturation
- Saturation then results in the injection of harmonic currents into the system (transformer becomes a significant harmonic source)
- Increase heating of magnetic components
- Audible noise
- Reactive power demand

DC INJECTION & PV

- Relations to Grid-Tied PV applications
- PV inverter converts DC output power from the PV panels and converting it into AC power.
- Hence the possibility that a DC component (offset) on voltage or current will appear and flow into the grid has to be considered.

MAIN TYPES OF INVERTER TOPOLOGIES

Topology	Description
Low Frequency Transformer	A low frequency transformer is implemented between the DC-AC converter of the inverter and grid connection.
High Frequency Transformer	A high frequency transformer is implemented on the DC side of the actual inverter. DC voltage is firstly converted into a high-frequency alternating voltage. This alternating voltage from the secondary side of the transformer is then again rectified and converted by the DC-AC converter into a 50/60Hz voltage.
Transformerless	No transformer used. DC-AC converter is connected to the grid without any galvanic isolation.

DC INJECTION

- DC injection limit varies across countries.
- Apart from the general agreement that excessive DC injection can cause problems, there has not been any consensus on what the limit should be.
- Accumulatively, multiple inverters in the system may compensate any DC injection from each other (instead of adding on constructively).
- It is also technically challenging to measure DC in the presence of large AC.

DC INJECTION LIMITS

Countries	Limits	Guideline / Standard Adopted
Japan	1% of inverter output	Japanese Technical Guideline for Grid Interconnection of Dispersed Power Generating Systems
Thailand	0.5% of inverter output	IEEE 1547
Australia	0.5% of inverter output	AS4777
Germany	1A	VDE 0126-1-1
United Kingdom	<2kW; 20mA each >2kW; 0.25% of AC rating (till further study is completed)	G83 Issue 2, G59 Issue 2
ASEAN	Will be coming up with a similar guideline following the IEEE 1547 (IEEE 1547 DC injection: 0.5% inverter output)	

DC INJECTION

- Then, there has been discussion to align to IEEE 1547 DC injection 0.5% limit and the formulation of a Distributed Resources Handbook.
- However this 0.5% limit if applied at larger PV inverter(s) output may exceed the DC tolerance values of certain distribution transformers.
- DC tolerance value varies between transformer.
- Hence, allowance of DC injection now is based on a case by case basis.

SIMPLIFIED ILLUSTRATION

- 1MVA 22kV/433V
  Eg. Distribution Transformer DC limit = <u>2A</u>
- 1MW PV Inverter of 0.5% DC injection
  0.5% * 1333A = <u>6.66A</u>
- <u>Assumption: DC adds on constructively</u>
- 6.66A > 2A (**limit exceeded on transformer**)

DC INJECTION

- One certain way to guarantee a null emission of DC components into the distribution grid is to use an isolation transformer.

TAKE-AWAYS & CHALLENGES

- Limitation of disturbance level should start from equipment level, hence careful assessment should be done at design stage
- Effect of larger scale Grid-Tied PV on voltage fluctuation/flicker and intermittency of supply
- DC injection; how to measure? Practical way of assessment? Practical limits?

The End.

Thank you for your kind attention.

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