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Harmonic Issues of AEP Welsh HVDC System

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SUMMARY

Rapid growth of consumer digital electronics in distribution systems is a common phenomenon all over the world. Digital electronics are mainly characterized by irregular consumption of reactive power and high level of harmonic generation. As a result, unless properly treated, these distorted currents and voltages will find their way into the supplying transmission network, thereby challenging industry standards regarding the levels of harmonics that can be permitted at the point of common connection. This is particularly prominent in cases where the fault level of the supplying grid is low, which is often the case for remotely located transmission facilities.

As a particularly challenging effect of harmonics, resonance between transmission system and shunt reactive devices can occur that results in equipment outages and degraded equipment life [1]. With continuous growth of digital electronics, suppressing harmonics in transmission grids has become significantly more important to help ensure trouble-free operation by electric utilities. Suppressing harmonics also brings the benefits of decreasing or altogether eliminating the losses induced by harmonic propagation in the grid, as well as preventing possible overloading of harmonic filters located in the grid, and malfunction of protective devices.

This paper introduces the challenges imposed by the growth of ambient harmonics in the operation AEP Welsh HVDC system and also describes a major project initiated to address this issue in an effective manner.

KEYWORDS

High Voltage Direct Current (HVDC), Back-to-Back Converter Station, PQ Guidelines, Harmonic Filters, Background Harmonics, Reactive Power, Weak AC System

1. Introduction

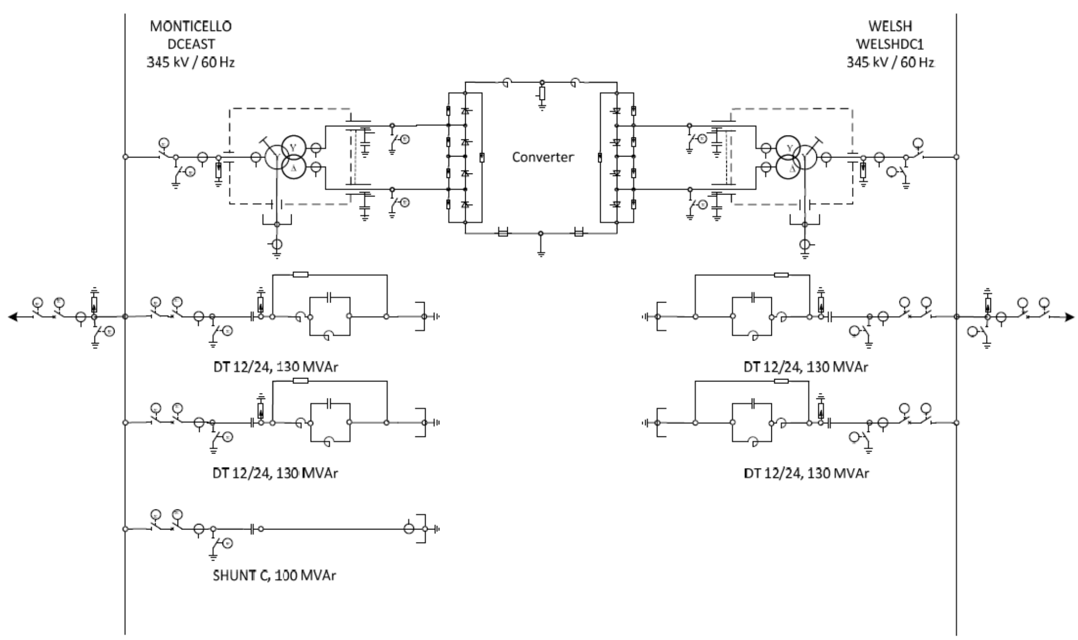
American Electric Power (AEP) is the Transmission System Operator of the Welsh 345 kV HVDC Back-to-Back Converter Station (Figure 1) connecting the Welsh Power Plant in Southwest Power Pool (SPP) and the Oncor Electric Delivery substation at the Monticello Steam Electric Station in Electric Reliability Council of Texas (ERCOT).

During the last five years, the converter station has experienced operational malfunctions of some of the measuring and protection equipment. Also overloading of harmonic filters has been reported when all three Monticello generating units are offline. During this event, the filter bank current has an unusually high 5th harmonic component causing the overcurrent protection to activate. The HVDC control system will prevent the tie operation when no filters are available.

Figure 1.

The Original Welsh HVDC Simplified One-Line Diagram

(ERCOT) (SPP)



The elevated 5th harmonic currents can cause thermal damage to the filter components, in particular the reactors. The cause of the 5th harmonic current is related to higher than normal system voltages, light loading of the transmission grid and certain system configurations that create a weak system. The origin of the ambient 5th order harmonic is unknown, but is thought to be related to semiconductor switching consumer loads, such as computer power supplies and industrial/commercial operations.

2. Emergence of Power Quality Concerns

2.1 Voltage Issues

Voltage problems on the ERCOT (Monticello) side of the converter station have been an issue since the station was commissioned in 1995. The converter station was designed for a nominal voltage range of 328 kV to 362 kV. Oncor, in an attempt to boost the voltage in Dallas/Fort Worth area, operates the Monticello bus at high voltages (Maximum of 355 kV). This can result in an even higher voltage on the HVDC bus due to the combination of high voltage at Monticello, light loading of the transmission system, filter operation and active power transfer level of the converter. The voltage issues are most prominent in the months of February to May. A lightly loaded transmission system changes the ratio of line capacitance to load inductance. Under certain conditions, the combination of line capacitance of the 16-mile transmission line connecting Monticello Station to Welsh HVDC and the capacitance of the filter banks causes the bus voltage at the converter station to rise as much as 6 kV above that of the Monticello bus. The problem normally occurs when the station is transmitting power to ERCOT and the converter is lightly loaded. The high voltage can be counteracted to some extent by the converter controls. The converter can change the firing angle to consume more reactive power and lower the voltage, provided there are sufficient margins in the firing angle operating range. At low power transfers (below 100 MW), the firing angle is very close to its upper limit leaving no margin for voltage control. The high AC voltage can cause the following issues:

- reduced life of switchyard equipment;
- suboptimal efficiency operation; and
- filter overload/tripping and the HVDC tie shut down.

2.2 Harmonic Issues

Elevated 5th harmonic currents have been observed in the filter banks under the same conditions that result in high bus voltage. Filter banks are designed to be a low impedance path to ground for the 11th, 13th, 23rd and 25th harmonics. These are characteristic harmonics generated by thyristor switching in the converter bridge [2], [3]. The filters are tuned broad enough to provide a low impedance path for the 5th harmonic. The issues appear to be magnified at higher voltage levels when one or more transmission lines, or generating units, are out of service and the AC system is weakened. The additional harmonic current added to the fundamental current can exceed the trip set point on the filter overcurrent relays.

To mitigate the problem, alarms were installed to alert the dispatchers when the HVDC tie goes into "Voltage Limit Control." This is the first indication that the bus voltage is above acceptable limits and that a filter trip may be imminent. The switching point of the second filter bank was raised to help keep the bus voltage from rising by forcing the VAR exchange with the transmission system to be more inductive. These changes helped mitigate the issue with only occasional nuisance trips of the filter banks over the last 20 years. To address the issue permanently, AEP initiated an extensive analysis that is explained in this paper.

3. Power Quality Guidelines

Guidelines have been established in the industry to limit harmonic currents that can be injected into a power system by distortion-producing facilities, such as nonlinear loads of electricity consumers and FACTS devices used by electric utilities. Limits also exist on harmonic voltage distortion that can appear at locations where these facilities are connected to the system, or elsewhere in the grid due to harmonic propagation away from the source. Of particular concern are resonant conditions involving the system and power-factor correction equipment common at such facilities. If present, resonant conditions can manifest themselves as excessive voltage distortion levels, even if the injected harmonic currents remain below the specified limits.

In the U.S., IEEE Standard 519 [7] provides a basis for harmonic distortion limits to be applied at any given system location, including distribution (120 V through 69 kV), subtransmission (69 kV+ through 161 kV) and transmission (above 161 kV). Harmonic current limits are site-specific and are based on the rating of the source of distortion with respect to short-circuit capacity of the power system, as well as on the voltage class at the point of connection. Harmonic voltage limits depend only on the system voltage class. Lower limits apply to larger distortion sources, operated at higher system voltages, because the associated effects can propagate over longer distances. Both current and voltage distortion limits are set for all individual harmonics and their composite quantity (root-mean-square) known as Total Harmonic Distortion (THD).

For the Welsh HVDC 600 MW tie, linking the ERCOT and SPP 345 kV systems, the system/HVDC capacity ratios are approximately 10 and 25 respectively, during normal system operation. These ratios decline by about one-half for a critical system contingency. Accordingly, the following harmonic distortion limits are applicable at the Welsh HVDC tie:

Table 1.

IEEE Standard 519 Harmonic Distortion Limits

Harmonic Order (H)	IEEE Standard 519 Harmonic Distortion Limits Current (%)*	Voltage (%)**
H < 11	2.0	1.0
11 ≤ H < 17	1.0	1.0
17 ≤ H < 23	0.75	1.0
23 ≤ H < 35	0.3	1.0
35 ≤ H	0.15	1.0
THD	2.5	1.5

*Expressed in percent of Welsh HVDC nominal current rating (600 MW, 1004 A).
(Limits recommended for system/distortion source capacity ratio below 50.)
**Expressed in percent of nominal voltage at Welsh Station/system interface.
(High-voltage systems are allowed up to 2.0% THD from an HVDC terminal.)

Experience indicates that background harmonics in the ERCOT and SPP systems served by the Welsh HVDC tie can reach high levels, overloading the associated harmonic filter and tripping it along with the tie. Harmonic voltage levels substantially above the specified limits were observed. In response, a project was initiated to develop a long-term solution for this recurring problem.

As part of the project, it was decided to establish Harmonic Performance Requirements based on two guiding principles: (i) reliable operation of the HVDC tie with no unplanned tripping of any station component due to harmonics, and (ii) compliance with the IEEE Standard 519 limits by the tie-originated distortions, as calculated at the interface with the ERCOT and SPP systems. (Subsequently, in view of high background harmonics, the latter requirement was relaxed recognizing that a system-wide approach will be a more effective strategy for harmonic mitigation at Welsh Station.)

Comprehensive measurements of local area electrical distortions were obtained to support the design of additional harmonic filtering at the station. These measurements are described in the following section of the paper.

4. Harmonic Measurements, Analysis and Studies

Since the transmission network has a complex structure and its impedance varies with frequency and system condition in a nonlinear fashion, such harmonic study would require a detailed computer model and elaborate analysis of the network [4], [5], [6]. Hence AEP initiated a project to investigate the harmonic issues in the Texas system.

In this project, a large portion of ERCOT and SPP around the HVDC was modelled using PSCAD. A frequency scan was done from 60 Hz up to 3 kHz for harmonic analysis and was verified by field harmonic measurements that were done during a span of two years.

The task is divided into modelling of the linear transmission network components and modelling of the nonlinear transmission network components that are installed directly on the transmission level, namely the transformer core nonlinearities and the HVDC converters.

While modelling the linear, frequency dependent components in the harmonic domain, priority is given to modelling the transmission lines, especially the effects of distributed parameters. All other shunt and series linear elements are also considered and the aspects that have to be included in the models are pointed out.

Consequently, the amplification and resonance of all different harmonic levels were considered and studies for all system conditions and filter combinations to pin point the highest level harmonic and the condition it is associated with.

It was later observed that the ambient 5^{th} harmonic is amplified significantly when only one filter is connected and no generator units are available on the Monticello side of the tie.

4.1 Harmonic Measurements

The background distortion level for low order harmonics is one of the important parameters that determines the design and performance of the filters. Choosing a high value for the background distortion level of the low order harmonics would drive the design margins of the filter components high, thus impacting the cost of the filters. In contrast, choosing a low value would impact the reliability of the whole tie by means of low design margin to withstand some unpredicted high levels of distortions that may arise in the future. To understand the severity and trends of the low order harmonics distortion levels, power quality recording equipment was setup on both terminals of the tie. Recorded data was used to track trends of individual low order harmonics, determine if high levels of distortions can be correlated with switching of local or remote equipment (indicating series or parallel resonance/amplification), determine if the maximum distortion levels show up right after switching of the local shunt branches (thus attributing high distortions to switching transients of the local shunt branches), etc. In other words, recorded data was used to eliminate outliers and filter "bad" data that cannot be correlated with real system behavior. Correlation of high distortion levels with switching of local or remote equipment posed as a challenging task to the team because of the fact that AEP doesn't own a majority of the network on both sides of the tie, thus relying on collaboration with neighboring transmission utilities.

Based on the analyses of the recorded data, table 2. summarizes the low order harmonics distortion levels used as input to the design and performance study of the HVDC filters.

Table 2.
Applied Low Order Harmonic Distortion Levels

Harmonic order	ERCOT side (%)	SPP side (%)
3rd	1.02	0.37
5th	3.64	2.17
7th	1.19	0.53
9th	0.18	0.20
11th	0.44	0.18

4.2 Analytical Studies and Performance Criteria

4.2.1 System model used for calculation of Z_{system} as a function of frequency

To properly analyze the performance and rating requirements of a given HVDC design, a robust and accurate network model on both sides of the HVDC is required. Due to the proprietary nature of the generator model data in the vicinity of the HVDC tie, the system characteristics on both sides of the HVDC terminals were used in a form of harmonic impedance (sequence impedance magnitude and angle) as a function of frequency for various system topologies (i.e. various combinations of shunt devices turned on and off, generator units on and off, etc.). Extensive PSCAD simulation was setup to calculate the network impedance as seen from the HVDC terminals, in which critical equipment was identified and placed in a list. A custom PSCAD component was created to cycle through the list and arrange all of the possible combinations for the network topology as shown in Figure 2.

Figure 2.
Simplified Scheme for HVDC, Ambient Harmonic Sources and Network Interactions

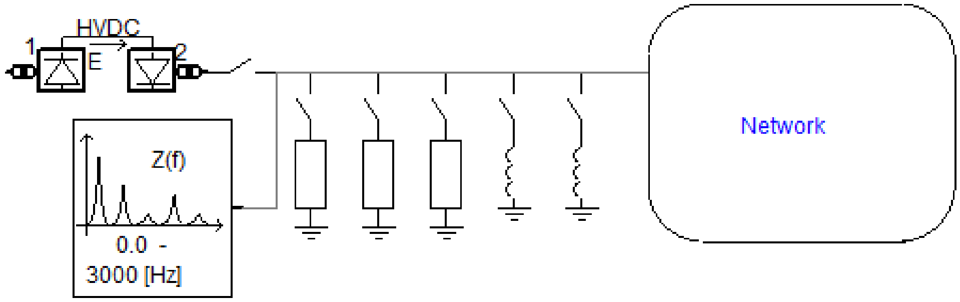
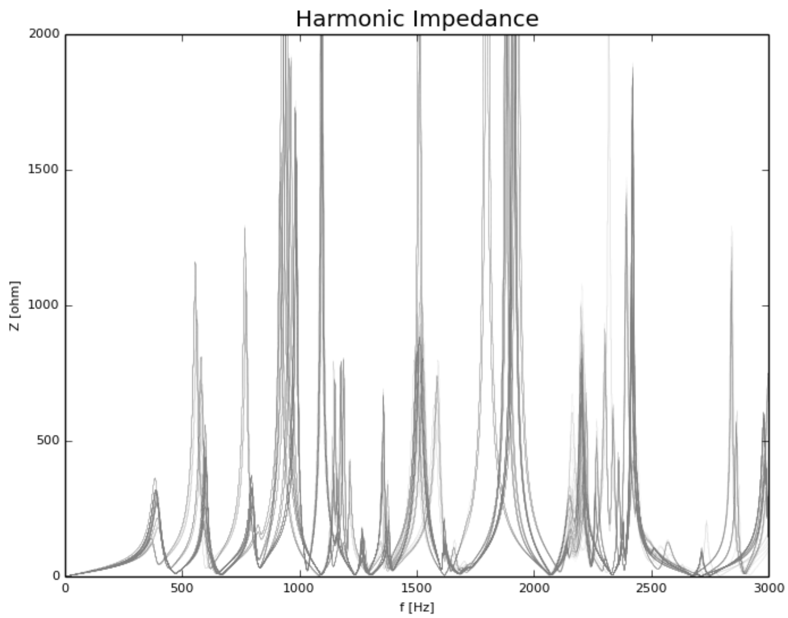


Figure 3.
Impedance traces for ERCOT side of HVDC



A PSS/E power flow case was reduced and translated into a PSCAD case by ETRAN software in which transmission lines owned by AEP were modeled using a frequency dependent phase model and the rest of the transmission lines were modeled using the Bergeron model. Generators were converted with ETRAN using DYR file. Loads connected directly to high voltage bus (345kV, 138KV or 69kV) in the translated PSCAD case were substituted with equivalent motor load connected through a transformer. The idea of modeling the loads this way was to pronounce the system resonance during variation of the network topology. Figure 3. shows positive sequence impedance magnitude traces for all of the network topology combinations.

4.2.2 Filter branches and reactor branches

Filter branches for the design and performance portion of the analysis were modeled by using lumped values for resistor, inductor and capacitor components. Reactor branches were modeled with lumped values for the resistance and inductance.

The harmonic AC filter performance calculations were carried out for both SPP and ERCOT side for all possible AC filter and shunt reactor/capacitor combinations consistent with the reactive power requirements.

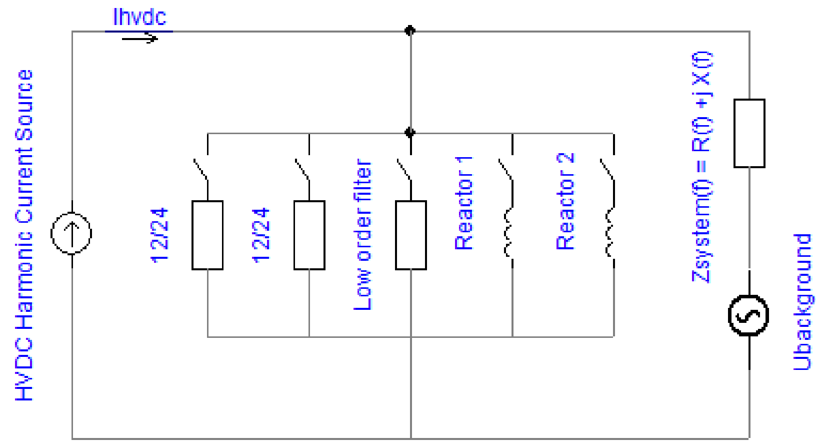
4.2.3 Performance criteria

Meeting of the harmonic distortion limits specified in IEEE Standard 519 [7] posed as a challenging task to the team due to the elevated levels of low order harmonic distortions. One option was to mandate full performance compliance to the limits specified in 519 and another option was to rate the internal components of the low order filter to withstand higher levels of distortion and mandate performance compliance to the limits specified in IEEE 519 only to the characteristic harmonics and make sure that any combination of the five shunt branches connected to either side of the HVDC terminal can reliably operate in system conditions with elevated low order harmonic distortion. Due to the complexity of the design based on the first option, a decision was made to define the performance criterion based on the second option.

4.2.4 Design of the low order filter

To design and install a low order filter to assist existing filters in conditions with elevated low order harmonic distortions and to compensate the reactive power of the low order filter, additional shunt reactors were required on both sides of the tie to help with voltage regulation at the HVDC terminals, when nearby conventional generation is offline. Figure 4. illustrates the final layout of the filter branches and shunt reactor branches, and which was used as a base for calculation of voltage magnification by low order background harmonic sources.

Figure 4.
Harmonics Amplification Calculations



Within the filter studies all the switching combinations of AC filter and shunt reactor/capacitor described in 4.2.2 were combined with the discrete harmonic impedance values for over many thousands network impedance data obtained in 4.2.1.
AC filter performance limits are based on calculated individual harmonic voltage distortion D_n and total harmonic voltage distortion THD level according relevant standards i.e. IEEE 519.

High level overview of the design workflow is illustrated in Figure 5. From Figure 5. it can be seen that the input data for the low order filter design and performance evaluation is the voltage distortion as defined in 3.1 and Z_{system} as outlined in 3.2.1, which is fed into the filter design engine. At this stage, amplification factors are calculated for various filter branch and reactor branch configurations, as well as current distributions for the low order filter internal components. Then the results are passed to the performance criteria block, which determines if the performance criterion is met. If the outcome is “Yes,” then the design can be considered final. If “No,” then the internal components of the low order filter are adjusted and looped through the filter design and performance evaluation block.

Figure 5.
High level overview of the design workflow

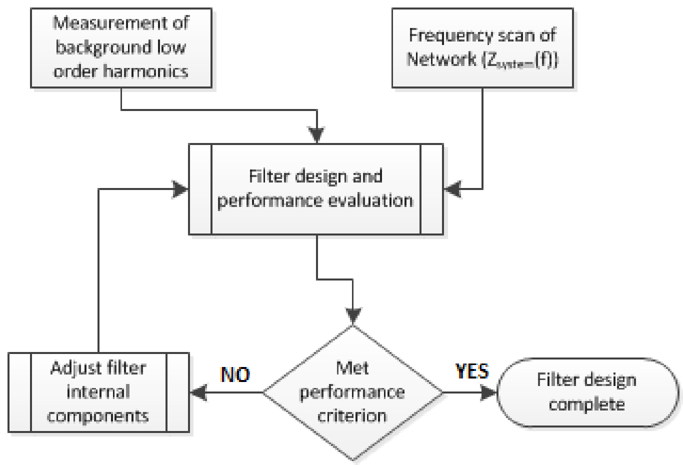
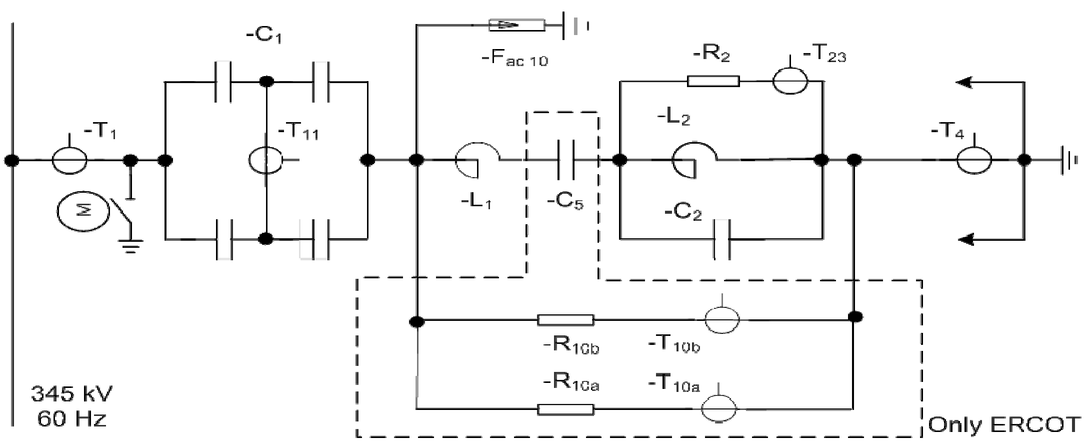


Figure 6 shows the single line diagram of the additional new Low Order Filters which are double tuned high pass damped filters each rated 100 MVar tuned to 5th/11th harmonic. The rating of the ac filter components are mainly determined by the high magnitudes of low order harmonics n = 3, 5, 7 and 9. It should be noted that the more severe harmonic impedances require higher energy ratings for the ERCOT side.

The additional tuning for 11th harmonic is needed since a reduced damping of HVDC converter harmonics is observed for the new harmonic network impedances adapted to recent changes in the topology of the AC systems.

Figure 6.
Single line diagram of new $5^{th}/11^{th}$ AC filters



5. Conclusion

This paper describes the challenges imposed by amplified background harmonics for AEP Welsh HVDC operation and shows how certain weak system conditions can cause amplification of ambient harmonics to intolerable levels. This paper also presents an overview of the process to perform the necessary measurements, studies and analysis to mitigate the issue and design additional harmonic filters and/or shunt reactors.

In the Welsh HVDC project, all system contingencies were considered with the worst (highest) ambient harmonics measurements to design the filters. This approach provides a robust and reliable design that maintains the harmonic levels within operable limits under all system conditions and also allows AEP to operate the HVDC without major concerns for ambient harmonic growth in near future. This approach is also suitable for application to other areas facing similar uncertainties.

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