RELIABILITY-ENHANCING, COST-EFFECTIVE TECHNOLOGIES FOR WIND POWER INTEGRATION INTO UTILITY POWER GRIDS

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Abstract—Wind power has become the world's fastest growing renewable energy solution, and with it comes some specific issues relative to integrating this intermittent power source into the utility's grid. The key issue for wind power integration into utility power grids is that the intermittent nature of wind can produce significant power factor problems. Since utility interconnection agreements typically specify a power factor level that must be maintained, power factor correction must be provided. The most common and most cost-effective means of power factor correction is switched shunt capacitor banks. Although switched shunt capacitor banks are required to provide the needed power factor correction, switching these shunt capacitor banks also has the potential to create utility power grid problems due to the voltage transients and the current transients which can occur as a result of adding these capacitor banks to the grid. Fortunately, a technology exists which can provide reliable, repeatable, cost-effective mitigation of these voltage transients and current transients associated with switching shunt capacitor banks and can do so without the need for or expense of current limiting reactors. A companion technology is available to provide integrated current sensing capability for these capacitor switching devices, enabling their inherent fault interrupting capabilities. This paper covers these technologies and the functions that they play in assuring that the integration of wind power into the utility grid is accomplished as seamlessly as possible.

I. WIND TURBINES, WIND FARM SITING, AND THE ELECTRICAL EFFECTS/CHARACTERISTICS OF THE POWER SYSTEM

Wind turbines are large induction machines which, when operating, introduce a significant amount of inductance into the power grid. This inductance creates a substantial draw down of the power factor from unity (1.0) or very close to unity—a situation which left uncompensated for would have tremendously detrimental effects to the grid and the loads connected to it. Clearly and quite logically, the utility to which the wind farm is connected would find an uncompensated-for draw down of the power factor and its associated negative consequences completely unacceptable. The correction of the power factor to return it to unity or very close to unity is accomplished through the addition of capacitance, with the objective of balancing the amount of capacitance supplied with the amount of inductance generated by the wind turbines so that the capacitance and the inductance effectively cancel each other out, allowing the power grid to experience a "null" effect of having the wind farm added to it. This capacitance takes the form of switched shunt capacitor banks located at the wind farm's substation.

Due to the fact that wind farms are most commonly located in remote areas and/or at the ends of long subtransmission, transmission, or EHV (extra high voltage) transmission lines that are; by their very nature; lightly loaded, these remote locations tend to experience higher than normal system voltages due to the inherent line capacitance. Before wind turbines can be added to the power grid this high voltage problem created by lightly loaded, long lines to remote areas must be addressed; and this is done by switching on one or more shunt reactors. The reactors are switched on to bring the system voltage down to the normal system voltage so that the wind turbines can start up and get connected to the grid. Once these wind turbines start up, get connected to the grid, and start generating power they are, as previously mentioned, induction machines; so it is at this point that the shunt reactors are switched off (as their duty has been successfully performed) and the shunt capacitor banks are switched on to provide the capacitance necessary to cancel the inductance generated by the wind turbines and to allow the system power factor to remain within its acceptable range (typically .95 lagging to 1.0 [unity power factor]).

II. SHUNT CAPACITOR BANK SWITCHING—A UNIQUE DUTY

Switching shunt capacitor banks is both an electrically difficult and mechanically difficult duty. The electrical difficulties occur in two forms—voltage transients and inrush currents (also known as current transients).

Voltage transients occur because when a shunt capacitor bank is added to the utility system the capacitor bank “looks” like a dead short (short circuit) to the system so the voltage collapses to zero and then “rebounds” to a value higher than the normal system voltage. These voltage oscillations continue until the capacitor bank and the utility system to which it is now connected equalize to like voltage values (i.e. the apparent dead short condition disappears). Normal system voltage is represented as 1 p.u. (per unit). Sensitive electronic equipment (computers, CNC [computer numeric control] machines, and variable speed drives) cannot typically accommodate per unit voltage values above 1.2 p.u. without sustaining some damage/loss of function (which is in direct proportion to the magnitude and duration of the over-voltage) or a change of state (such as a variable speed drive tripping off line). These problems make it readily obvious that the voltage transient issue must be addressed and handled by the shunt capacitor bank switching device.

Current transients occur for the same reason that voltage transients do; i.e. the shunt capacitor bank, once added to the utility system, appears as a short circuit so the system (source) wants to dump all of its current to the load (short circuit), the capacitor bank. The current rushes from the utility system (source) to the capacitor bank (load), but the capacitor bank returns some of this current to the utility system. This process, essentially a current “ringing” effect, repeats itself until the capacitor bank is fully charged. These current oscillations, more commonly called inrush currents or current transients, are very high magnitude (on the order of 20 kA), very high frequency (1000 Hz or more in many cases) currents; and these currents create significant potential for damage to other utility system equipment components (such as circuit breakers and power transformers, just to name a couple of examples). Suspicious failures of utility system equipment (a circuit breaker which is found to have its contacts welded in the closed position; a power transformer which has a core failure, a coil failure, or both; etc.) can in many cases be traced back to the high magnitude, high frequency inrush currents this equipment has experienced. Clearly here as well, these problems make it readily obvious that the current transient issue must be addressed and handled by the shunt capacitor bank switching device.

In addition to the voltage transient problem and the current transient problem, shunt capacitor banks applied in wind farm applications (and in most other utility system applications as well) are switched very frequently—often multiple times per day. Substation equipment such as circuit breakers and circuit switchers seldom see as many operations over their entire useful life as a shunt capacitor bank switching device would see in a single month; so, since their applications are such that circuit breakers and circuit switchers operate quite infrequently, their designs are based in part upon their assumed and intended mechanical duty. It would be quite atypical for a circuit breaker or a circuit switcher to be designed for the multi-time-a-day duty that is required by most shunt capacitor bank switching devices. In fact, shunt capacitor bank switching is in every way a special duty which is ill-suited to devices designed for other functions.

Circuit breakers are designed for two basic functions—line protection and bus protection—and two basic duties, relaying and reclosing. These duties and functions are what general purpose circuit breakers do. Circuit switchers are designed for one main function, power transformer protection, via one main duty, relaying. This duty and this function are what circuit switchers do. To use circuit breakers or circuit switchers for duties and functions other than those listed above require special purpose circuit breakers or special purpose circuit switchers, and in both cases these special purpose devices would be adapted technology, not designed-for-the-function/duty devices.

A long-life, transient mitigating (of both voltage transients and current transients), cost-effective shunt capacitor switching device is required.

III. AVAILABLE DEVICES FOR TRANSIENT MITIGATED SWITCHING OF SHUNT CAPACITOR BANKS

There are four types of devices available to perform the function of transient mitigated switching of shunt capacitor banks:

- Zero voltage closing (also known as synchronous closing) vacuum switches
- Synchronous closing circuit breakers
- Pre-insertion inductor circuit switchers
- Pre-insertion resistor capacitor switchers

Each of these will have their pros and cons examined to determine which device best serves the required function.

Zero voltage closing vacuum switches (See Figure 1.) have the advantages of low cost, compact size, and the ability to be mounted on the capacitor bank; but these advantages are more than offset by a long list of negatives, including:

- Poor history of reliability
- Multiple gap per phase interrupters at 34.5 kV and above (This is significant as the wind farm collector bus, where the shunt capacitor banks would be located, is a 34.5 kV application; and multiple gap per phase interrupters are mechanically more complex and inherently less reliable than single gap per phase interrupters.)
- Very limited fault interrupting capability (3 kA to 8 kA)
- Requires in-series reactors (circled in green in Figure 1 below) to limit the inrush currents to values within the vacuum switch's capabilities
- These series reactors required for use with the vacuum switches create power losses
- Series reactors create high frequency TRV (transient recovery voltage) and require bridging with capacitors to delay the onset of the TRV peak so that the protective device can win the TRV "race" (Winning the TRV "race" entails the protective device building dielectric gap strength across its interrupter contact gap faster than the TRV rises.)
- Multiple mechanisms, one per phase, are required to achieve synchronous closing
- Failure of one mechanism to operate can result in single phasing the capacitor bank
- Synchronous closing is inherently difficult to achieve repeatably over a large number of switching operations

Figure 1
Zero Voltage Closing Vacuum Switch (circled in red)
With In-Series Current Limiting Reactor (circled in green)

Synchronous closing circuit breakers (See Figure 2.) have the advantages of high interrupting ratings (20 kA, 25 kA, 31.5 kA, 40 kA, 50 kA, or 63 kA), integral bushing mounted current transformers, single gap per phase SF_6 gas interrupters, both local visual indication of gas system status and remote gas monitoring capability (low pressure alarm contact and trip on low gas contact), and making the circuit as well as breaking the circuit in its interrupters' SF_6 gas environment. Again, just as with the zero voltage closing vacuum switches, the synchronous closing circuit breaker's pros are more than offset by its cons, including:

- High cost
- Adapted technology rather than special purpose device designed for this required function and unique duty
- Multiple mechanisms, one per phase, are required to achieve synchronous closing
- Failure of one mechanism to operate can result in single phasing the capacitor bank
- Synchronous closing is inherently difficult to achieve repeatably over a large number of switching operations
- A voltage zero missed by more than 1 millisecond creates transients equivalent to there being no synchronous closing capability inherent in the device
- Bushing mounted current transformers can experience CT saturation which can cause either a delayed protection trip or a failure to trip under a fault current condition

Figure 2
Synchronous Closing Circuit Breaker

Pre-insertion inductor circuit switchers (See Figure 3.) have the advantages of

- Its inductor (with resistance) limits both the voltage transients and the inrush currents
- Provides visual isolation point (integral in-series disconnect switch) for capacitor bank inspection and/or maintenance

But once again, just like the other devices previously covered, the pre-insertion inductor circuit switcher's negatives far outweigh its positives. The cons include:

- High cost
- Adapted technology rather than special purpose device designed for this required function and unique duty
- External arcing in air during closing requires a large amount of substation space to minimize the possibility of arc migration to other substation equipment in the proximity and requires periodic outages to be taken to replace arcing horns/inductor insertion rods due to in-air capacitive arcing
- Has no fault closing rating
- Very limited fault interrupting capability (8 kA)
- Very limited number of available inductor (with resistance) sizes, making it difficult to achieve optimal voltage transient mitigation and current transient mitigation when using this device
- Requires either freestanding current transformers or extended-base-mounted current transformers to provide current sensing to enable its fault interrupting capability

Figure 3
Pre-insertion Inductor Circuit Switcher

Pre-insertion resistor special purpose capacitor switchers (See Figure 4.), quite unlike the other three available devices which provide transient mitigated shunt capacitor bank switching, has a long list of positive features, including:

- Special purpose device uniquely designed for the rigors of shunt capacitor bank switching
- Long endurance life (10,000 operations)
- Designed and tested to be restrike-free (Restrikes and the over-voltages that result from them are one of the leading causes of failure of zero voltage closing vacuum switches.)
- Pre-insertion resistors mitigate both voltage transients and inrush currents and do so more repeatably reliably than synchronous closing devices
- Wide range of standard resistors (6 Ω, 10 Ω, 12 Ω, 20 Ω, 30 Ω, 40 Ω, 80 Ω, or 90 Ω) and the ability to be furnished with virtually any custom size ohmic value resistor, making optimal voltage transient performance and current transient performance much more attainable when using this device
- 25 kA interrupting capability
- Multi-time 40 kA fault closing capability
- Single gap per phase puffer SF_6 gas interrupters
- Circuit making and circuit breaking occurs in the interrupter's SF_6 gas environment
- Compact design consumes a minimum of substation space
- Available with integral three-phase, non-contact, non-saturating current transformer to provide current sensing to enable its fault interrupting capability (See Figure 5 for a pre-insertion resistor special purpose capacitor switcher equipped with an integral three-phase, non-contact, non-saturating current transformer. See Figure 6 for an angled view of the current transformer only.)
- Has both local visual indication of gas system status and remote gas monitoring capability (low pressure alarm contact and trip on low gas contact)
- Ideally suited replacement solution for any existing wind farm shunt capacitor banks which are currently switched via vacuum switches
- This same device; less its pre-insertion resistors but furnished with its integral three-phase, non-contact, non-saturating current transformer; can also provide the switching and protection of the shunt reactors referenced in section I. of this paper [The pre-insertion resistors are not needed for the function of switching shunt reactors.] {See Figure 7 for this reactor switcher.}

A section view of a single line diagram depicting three 34.5 kV shunt connected capacitor banks switched and protected via pre-insertion resistor special purpose capacitor switchers; each equipped with an integral three-phase, non-contact, non-saturating current transformer; is shown in Figure 8. The obvious advantage of equipping each of these capacitor switchers with a three-phase current transformer is that in the event of a fault on one of the capacitor banks, that faulted bank can be tripped open, causing only the problem bank to be isolated from the system and removed from the power factor correction function being performed by these banks (as opposed to having to trip the entire bus in the event of a fault on one of the capacitor banks and the potential to have to perform multiple trip and reclose operations in order to isolate which of the banks is faulted).

The only real negative associated with this device is not a functional one but rather an awareness one—it is not a universally known solution among wind farm developers/wind farm substation equipment specifiers.

Figure 4
Pre-insertion Resistor Special Purpose Capacitor Switcher

Figure 5
Pre-insertion Resistor Special Purpose Capacitor Switcher
Equipped With Three-Phase Non-Contact Non-Saturating Current Transformer

Figure 6
Angled View Of Three-Phase Non-Contact Non-Saturating Current Transformer

Figure 7
Reactor Switcher Equipped With Three-Phase Non-Contact Non-Saturating Current Transformer

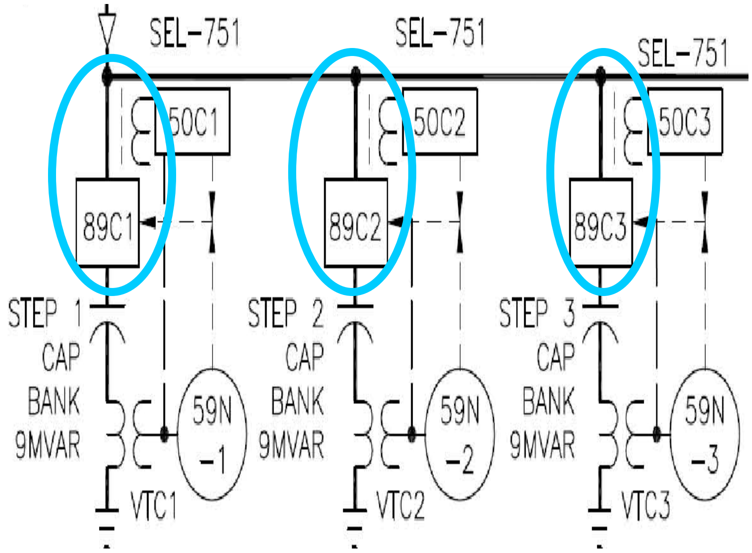

Figure 8
Single Line Diagram Section Of 34.5 kV Collector Bus's Three Shunt Connected Capacitor Banks Which Are Switched And Protected Via Pre-insertion Resistor Special Purpose Capacitor Switchers, Each Equipped With A Three-Phase Non-Contact Non-Saturating Current Transformer (Capacitor switchers in above diagram are depicted as 89C1, 89C2, and 89C3. They and their current transformers are circled in blue above.)

IV. CONCLUSION

Of the available technologies reviewed, wind farm integration into utility power grids can best be accomplished using pre-insertion resistor special purpose capacitor switchers to switch the shunt capacitor banks to provide the required power factor correction; and these pre-insertion resistor equipped capacitor switchers can be furnished with integral three-phase, non-contact, non-saturating current transformers to enable the capacitor switchers to provide bank protection as well as long-life, transient mitigated switching of both voltage transients and current transients. This same capacitor switcher/current transformer combination, less the pre-insertion resistors, can also be furnished to switch and protect the shunt reactors used in the wind farm's substation.

V. BIOGRAPHY

David Childress received his Bachelor of Science degree in Engineering from Mississippi State University in 1991. He joined Siemens Energy & Automation in 1991 as an application engineer responsible for circuit switchers and disconnect switches and later joined Southern States in 1997 holding positions of regional manager, international sales manager, product manager, and marketing manager. In these various capacities he has been responsible for all of Southern States products (disconnect switches, power fuses, switch operators and accessories, and SF_6 switching and protection products [including circuit switchers, capacitor switches, and full load break/loop break/line drop/cable drop/magnetizing current breaking interrupters]). He is presently the marketing manager of SSIPower LLC, a Southern States Company responsible for the introduction of power electronics solutions for the electric power industry—the first of which is a three-phase, non-contact, non-saturating current transformer. He is a member of IEEE and of the Power Engineering Society; a multi-published technical paper author; an author of over 100 catalog flyers, catalog bulletins, and other technical/product related documents; and co-author of the Electric Power Substations Engineering Handbook-Second Edition's chapter entitled "High Voltage Switching Equipment".

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