Applications in the Electric Power Industry based on Multi-Service Optical Transport Network

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Abstract. Transmission technologies are crucial to the automatic electric power systems in the smart grids. The goal is the higher bandwidth and reliability, just as in power line communication, microwave transmission, and the latest optical fiber communication. Based on the time division multiplexing, the fiber communication develops from the plesiochronous digital hierarchy and the synchronous digital hierarchy to optical transport network. The system can transmit the signal securely through hard pipes. Based on the synchronous digital hierarchy, optical transport network and the packet transport technologies, the MS-OTN is expected to offer secure, reliable, and flexible transmission for future electric power services.

Keywords: Smart Grid, MS-OTN, Hard Pipe

1. Introduction

In 2011, the State Grid Corporation of China (SGCC) adopted the first 220 kV smart substation. At the end of 2015, the SGCC has built 5182 smart substations and planned to build another 8000 smart substations by 2020 [1-2]. Fiber communication contributed heavily in this process of automating power transmission and transformation. SDH (synchronous digital hierarchy) supports the tele protection and dispatching with physical isolation, high reliability, and low latency. OTN (optical transport network) provides the high-bandwidth and efficient transmission of various services, such as video, office, and sales [3]. The next-generation platform MS-OTN (Multi-Service Optical Transport Network) absorbs the advantages of SDH and OTN and simplifies the network architecture for the next five-year development [4].

2. Existing Smart Grid Transmission Solution

2.1. Current Situation
In Figure 1, it is showed that the transmission network for smart grid communication consists of two SDH planes (A and B) to carry production services in zones I and II \[^{5-6}\]. While the backbone network uses OTN to transmit integrated data services in zones III and IV. The maximum rate at an SDH line port is limited to 10 Gbit/s. E1 private lines carry services such as tele protection and dispatching telephone, and ETH over SDH (EOS) private lines carry dispatching data services. In the early stage, only 10G OTN backbone networks were built to carry integrated data private lines.

**Figure 1.** Power transmission network

2.2. Problems and Solutions

2.2.1. Bandwidth. Smart grids incorporate emerging services, such as Internet of Things, video surveillance, and 5G, to gain further development. These services require the higher bandwidth, which beyond the 10G capability of narrowband-based SDH. In this case, OTN is introduced to raise the port rate to 100G, 200G, and even 400G. From 2012, 100G ports have replaced 10G ports to become the most cost-effective and commonly used ones in the industry \[^{7-8}\].

2.2.2. Multi-Service Transmission. There are dozens of services in a power grid. First, the traditional narrowband services are required, such as the tele protection, security and stability, SCADA, PMU, EMS, and the dispatching telephone in zones I and II. They require high reliability, low latency, and physical isolation. Then the large-bandwidth data services are needed, such as office, video calls, and sales. There are also new services such as Internet of Things, intelligent monitoring, intelligent inspection, and 5G. Conventionally, SDH networks offer 2M–1G private lines and OTN networks focus on higher than 1G private lines. 2M–100G integrated transmission is lacked.

3. MS-OTN and Its Electric Power Applications

3.1. Introduction

MS-OTN can flexibly carry 2M–100G services, which can be transmitted in an SDH private line of 2 Mbit/s to 1 Gbit/s, an OTN private line of higher than 1 Gbit/s, or an elastic PTN MPLS-TP channel \[^{9-10}\]. In addition, the OTN framer encapsulation technology is used to increase the port bandwidth from 10 Gbit/s to 400 Gbit/s. The optical-layer WDM (wavelength division multiplexing) technology further enhances the bandwidth to 100 Gbit/s or so many times to accomplish more transmission targets. MS-OTN is compatible with IEEE 1588v2 and ITU-T G.8275.1/ to meet 5G and power grid time synchronization requirements \[^{11}\].

2
3.2. Multi-Plane Unified Switching
MS-OTN supports unified cross-connections on the VC, PKT, and ODU/OSU planes. A set of MS-OTN devices can function as SDH, OTN, and PTN devices which access to the SDH PCM/E1/STM-N, ETH, and OTN services. EOS services are transmitted over 2M~1G granularities, and EOO services over 1G~100G hard pipes of ETH private lines and networks\textsuperscript{[12-13]}. MPLS-TP adds flexibility to ETH private lines and networks. SDH line boards and smart OTN (SDH/PKT/OTN) hybrid intelligent boards are available\textsuperscript{[14]}. A pair of optical fibers is used to carry services on multiple planes. The system block diagram is shown in Figure 2.

Figure 2. Unified MS-OTN platform

3.2.1. SDH plane
MSTP devices are equivalent to SDH tributary/line boards and a VC switching plane. The SDH plane provides all the MSTP functions and is compatible with the MSTP devices\textsuperscript{[15]}. In this plane, the SDH line interconnection, SDH SNCP, MSP, and ASON protection are available.

3.2.2. Hybrid planes
Smart OTN line board: OTN framer encapsulation is used on the line side. The OTUk and OTUCn interfaces works frequency at 2.5 Gbit/s, 10 Gbit/s, 100 Gbit/s, 200 Gbit/s, and 400 Gbit/s are supported which over ten times larger than the traditional SDH interfaces. The hard pipe-based timeslot isolation is used to transmit SDH, PTN, and OTN signals in different ODUk channels.

In the SDH plane, the VC-12, VC-3, and VC-4 signals are carried in hard pipes. Timeslots are bound to carry any 2M~10G services. The traditional E1, PCM, and ETH low-bandwidth pipes are remained.

In the PKT plane, the services at any granularity are transmitted in soft pipes of MPLS-TP. The soft pipe statistical multiplexing is supported, implementing bandwidth convergence of ETH private lines. Pipes can be shared in ETH private networks.

In the OTN plane, the traditional 1.25G ODUflex hard pipes are used. Any tributary services of traditional OTN, such as large-granularity STM-N, ETH, video SDI/DVB-ASI, storage FC16G and FC32G are transparently transmitted. In addition, 2.4M OSUflex hard pipes are introduced to flexibly carry E1 and ETH services. When the SDH industry lacks momentum, OTN can incorporate SDH services.

3.3. Hard Pipe Isolation
MS-OTN inherits VC hard pipes from SDH. The transmission rate is fixed at 8000 frame/s. Through byte interleaved multiplexing, the transmission rate of a fiber line is improved. Higher-order VC-4 and
lower-order VC-12/VC-3 granularities are used, and fixed bandwidth is occupied. When EOS is used, multiple VC granularities are bound to carry different ETH private line services. VC switching uses the circuit switching architecture, which provides a fixed rate and fixed latency without congestion.

On the other hand, the MS-OTN inherits the ODUk/ODUflex hard pipe switching of OTN. In this mode, byte interleaved multiplexing is also used. The frame structure is fixed at four rows and 4080 columns, where transmission rates can be improved by adjusting the frame rate. As for mapping and multiplexing, the user can either map the multiplexed lower-order ODUk signals into higher-order ones via byte interleaving, similar to VC. At the same time, the user can multiplex ODUflex signals into ODUCn signals similar to STM-N. The latter cuts mapping paths and lowers the latency.

3.4. Coherent 100G for Smart Grid

The single-wavelength transmission rate of backbone networks evolves from 10 Gbit/s to 100 Gbit/s. However, due to the non-linear effect of optical fibers, the NRZ (non-return to zero) technology causes the baud rate at 100G transmission rate to increase. The negative impact the OSNR (optical signal-to-noise ratio) performance in the long-distance transmission. In this case, the PDM-QPSK (polarization division multiplexing-quadrature phase shift keying) modulation and the coherent demodulation need to be used to reduce the baud rate and improve the single-wavelength transmission rate.

PDM-QPSK modulates the orthogonally polarized light, which means that the SOP (state of polarization) rotation must be tracked during coherent demodulation. In buried cable environments, SOP is mainly affected by vibration, and the rotation is less than 1M rad/s. The OPGW (optical fiber composite overhead ground wire) is usually used for power transmission and transformation. In thunderstorms, OPGW's SOP tolerance is increased to 2M to 8M rad/s or even higher.

To comprehensively adopt 100G communication systems, coherent optical modules need to be innovated to tolerate the SOP during thunderstorms.

In this paper, the coherent 100G optical modules from mainstream vendors was studied and optimized the optical parameters of the 100G PDM-QPSK format. The results show the relationship between the penalty and the transmission rate. It is shown in Figure 3.

![Figure 3. OSNR penalty and SOP tolerance](image)

It is expected that with a certain OSNR penalty of 1 dB, 3.5 dB, and 7.5 dB, the SOP tolerance could be 5M, 8M, and 10 M rad/s respectively.

According to the actual applications, the test with 1.5 dB penalty and 5M rad/s tolerance, or 4 dB penalty and 8M rad/s tolerance, the 24-hour bit error test can be passed. The test results are shown in Figure 4.
Figure 4. Bit error test of coherent modules

From Figure 4, the commercial use is currently not available when the tolerance is 10M rad/s due to insufficient vendor capabilities.

3.5. MS-OTN Architecture for All-Service Transmission

MS-OTN simplifies the architecture into two planes to carry all services in a power grid. In the MS-OTN network, the traditional architecture of SDH planes combined the OTN network into two planes and supporting all the PCM, PDH, STM-N and the ETH services.

In the stability control over E1 private line, the E1 electrical and optical interfaces are used. To deliver fixed and low latency, security, and reliability, the SDH plane of MS-OTN is used. Considering the required bandwidth (less than 50 Mbit/s) and sensitivity on security and reliability, EOS hard pipe private lines on the SDH plane are used.

The interface bandwidth exceeds 1 Gbit/s, so 1.25G OSUflex hard pipes on the OTN plane are used. In addition, OTN encapsulation protects ETH packets to ensure high ETH private line security. The MPLS-TP private line or network on the packet switching plane can be used to implement ETH bandwidth convergence and statistical multiplexing with high efficiency.

4. Conclusion

In the smart grid era, communication technologies are innovated to automate the power transmission and transformation, distribution and the distributed energy. MS-OTN has the characteristics of the high-reliability, low-latency and the all-service communication in the electric power industry. In the
future, this technology will cope with large SOP tolerance for the coherent 100G system in the actual harsh application environment.

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